



UNIVERSITY
OF OREGON

Tutorial Lecture: **Semiconductor Photoelectrochemistry and Solar Water Splitting**



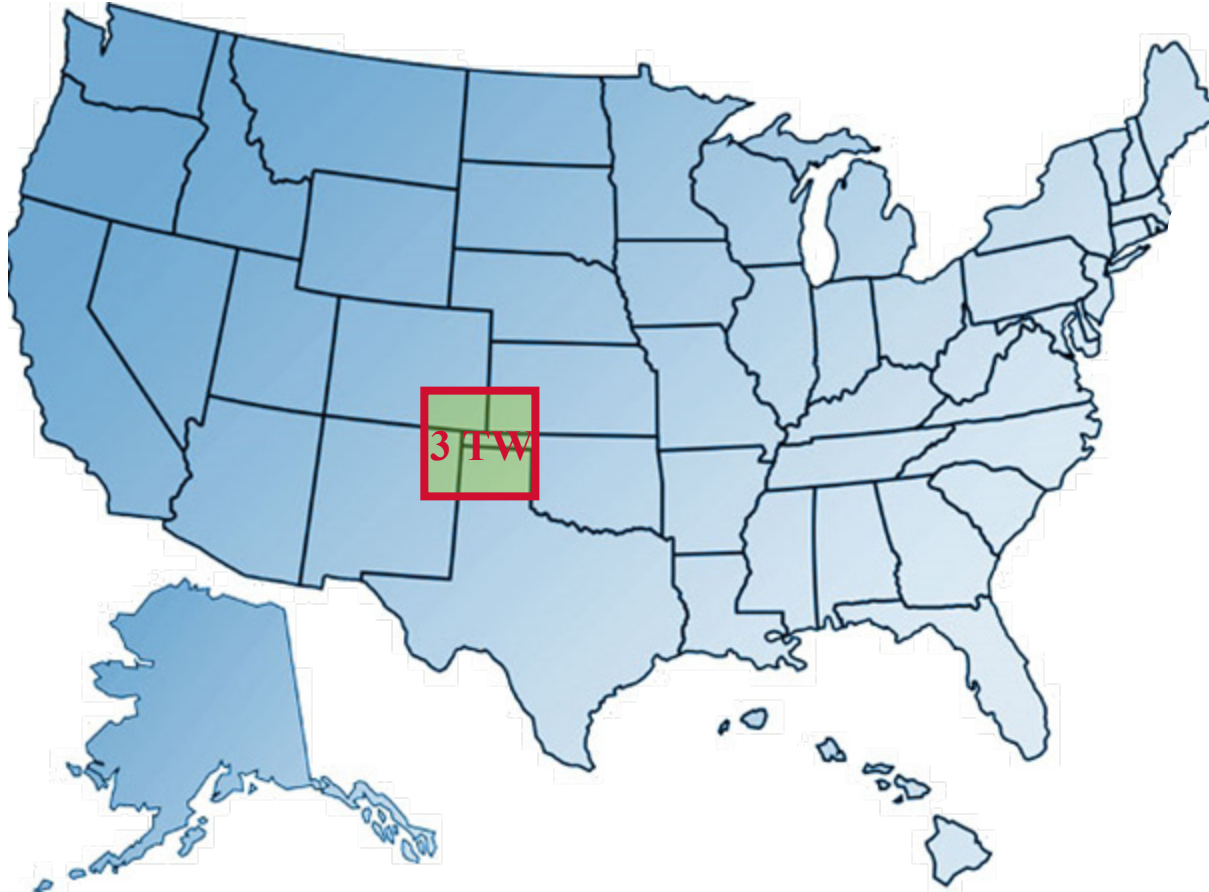
Mt. Hood Oregon

Shannon W. Boettcher
Asst. Prof. of Chemistry
University of Oregon
Eugene, USA





Motivation: Powering the Planet



**Global power consumption:
~18 TW**

Worldwide potential*:

Wind < 4 TW

Biomass < 5 TW

Hydro < 1.5 TW

Geothermal < 1 TW

Solar ~ 120,000 TW

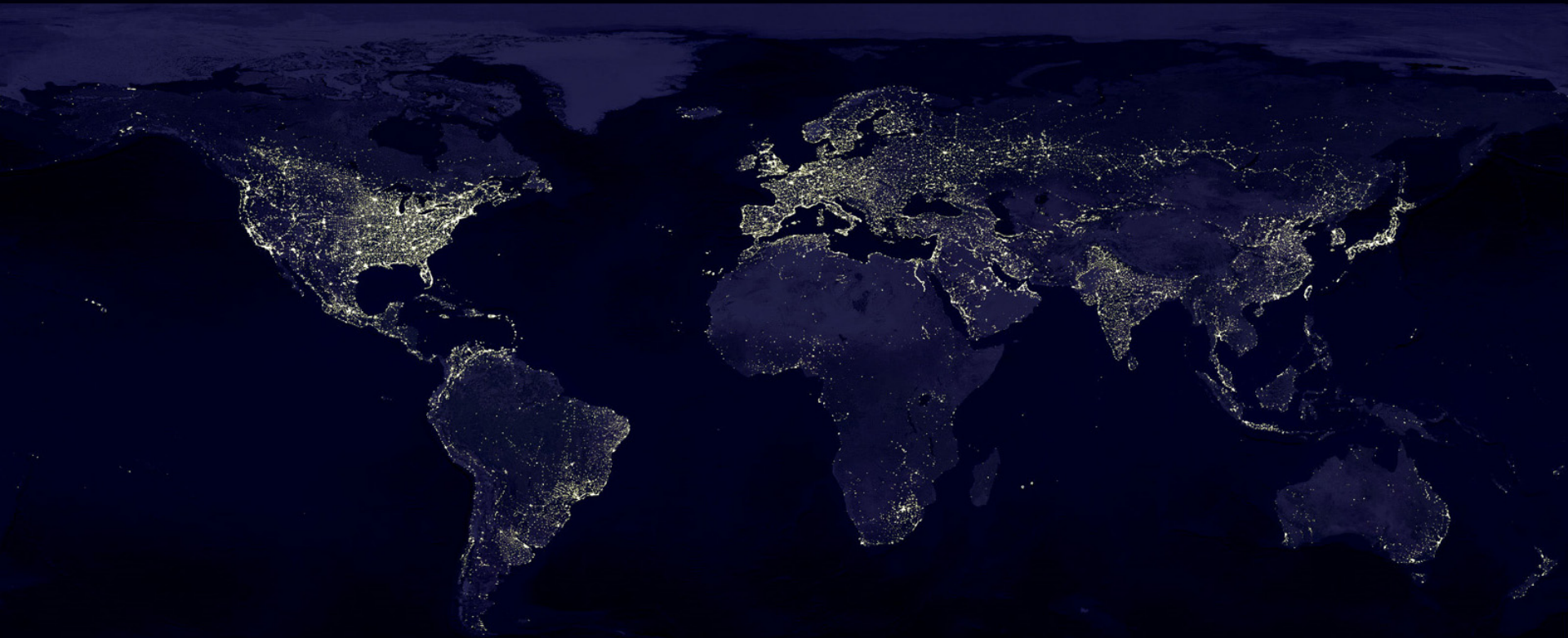
*Lewis, *MRS Bulletin*, (32) 808 2007.

Solar is the only renewable source capable of providing 20-50 TW of power worldwide.

Solar Energy Challenges

Solar Electricity > 15 ¢ per kWh (sunny climate, large installation)

Industrial Electricity ~ 5-10 ¢ per kWh

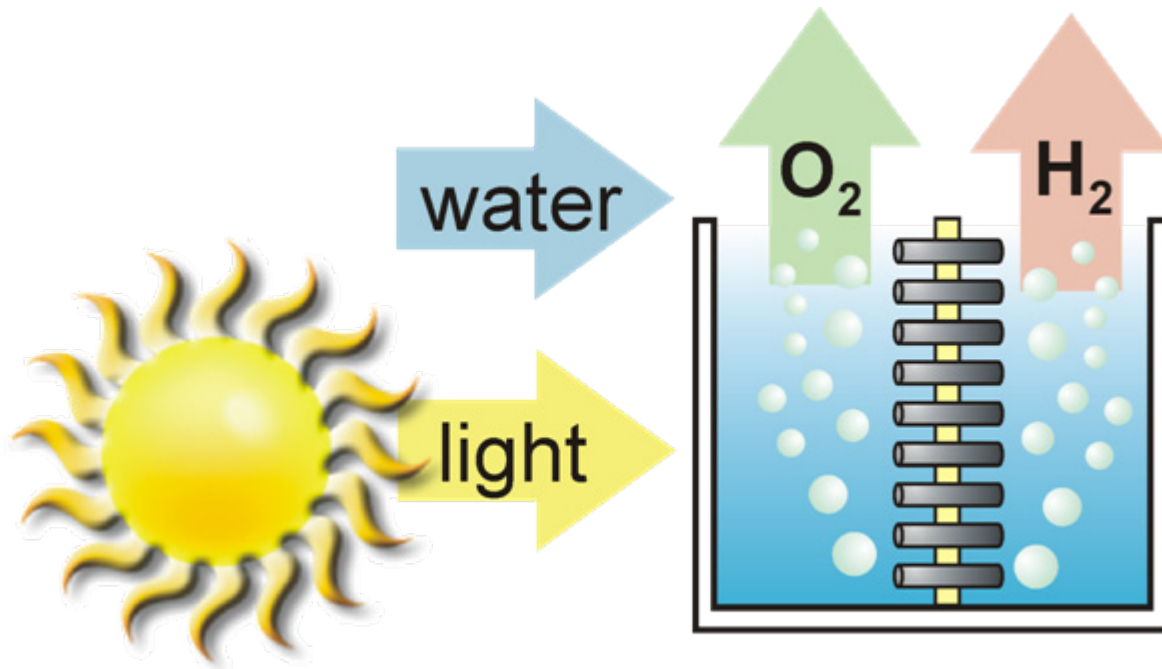


Cost of solar energy must be reduced to contribute significantly.

We must store that energy.



Vision for Storage: fuel from sunlight and water



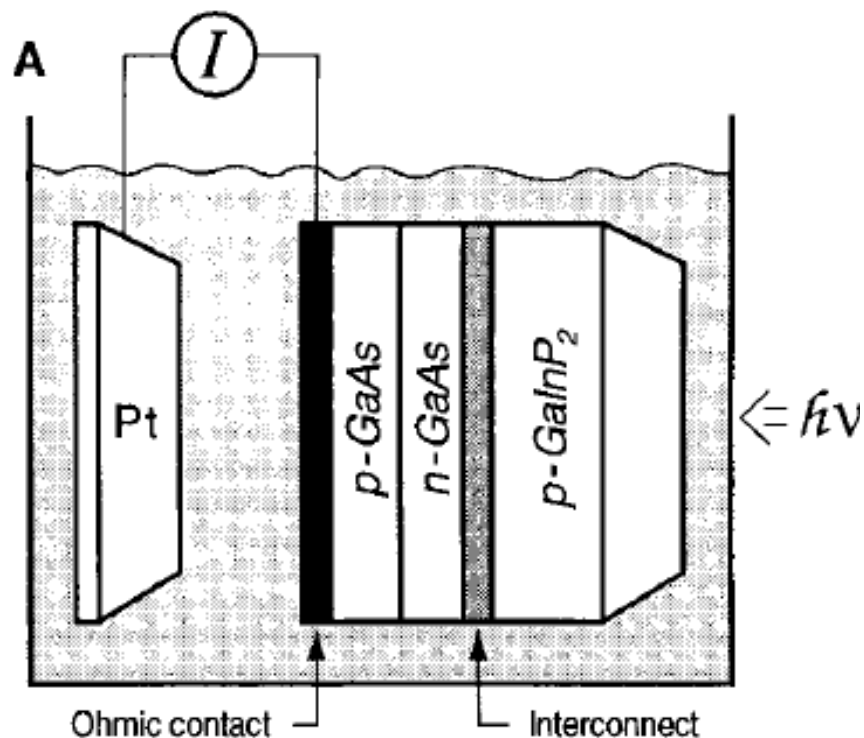
Advantages:

- no wires / external electronics
- low-cost semiconducting absorbers
- direct energy storage in chemical bonds
- H₂ for fuel cells, turbines, liquid-fuel synthesis from CO₂
- closed-loop cycle

Disadvantages: Difficult to find right materials and to scale.

PEC H₂ production can work

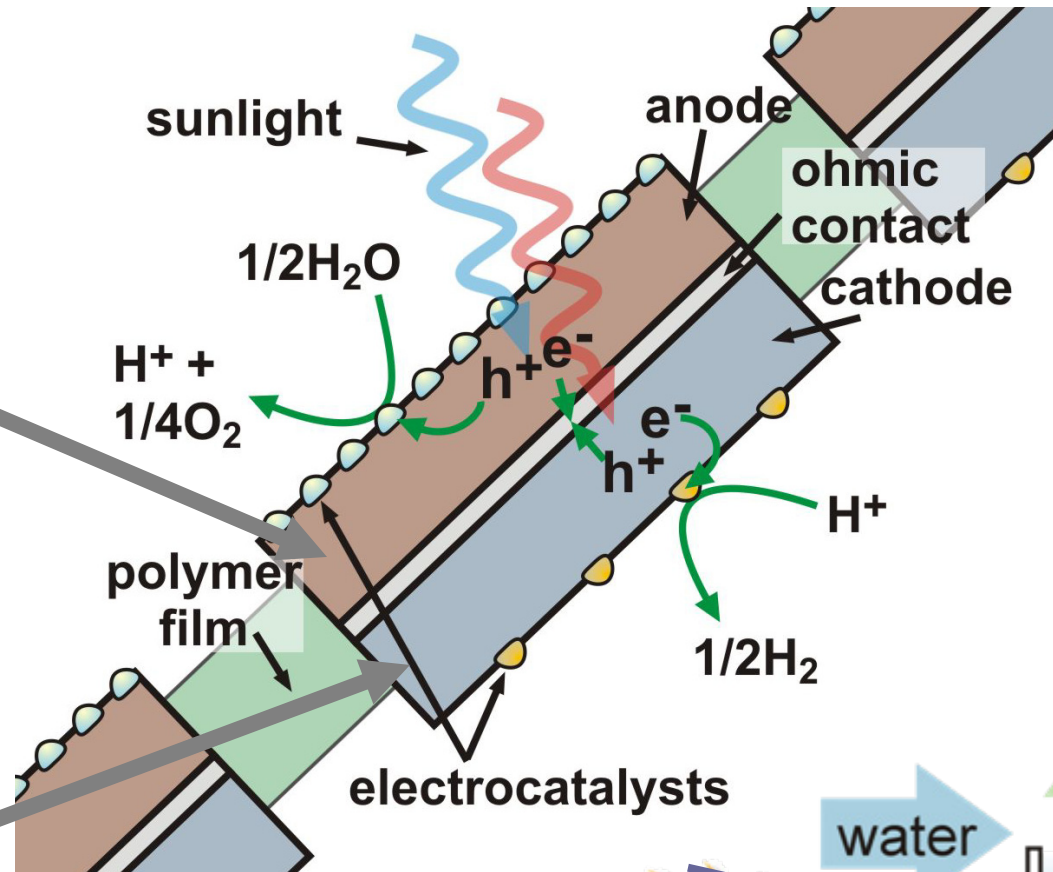
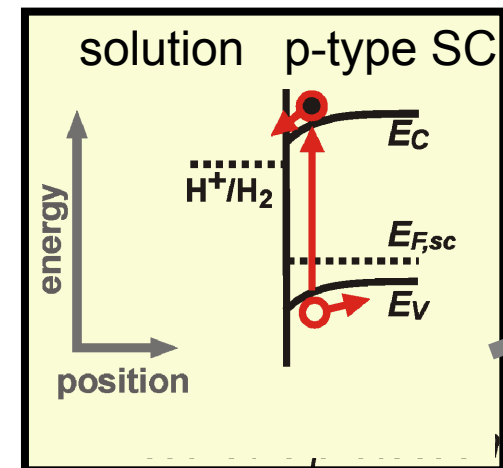
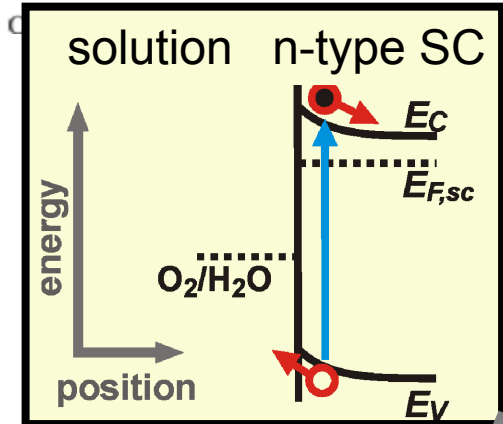
- [NREL Photoelectrolysis.mp4](#)



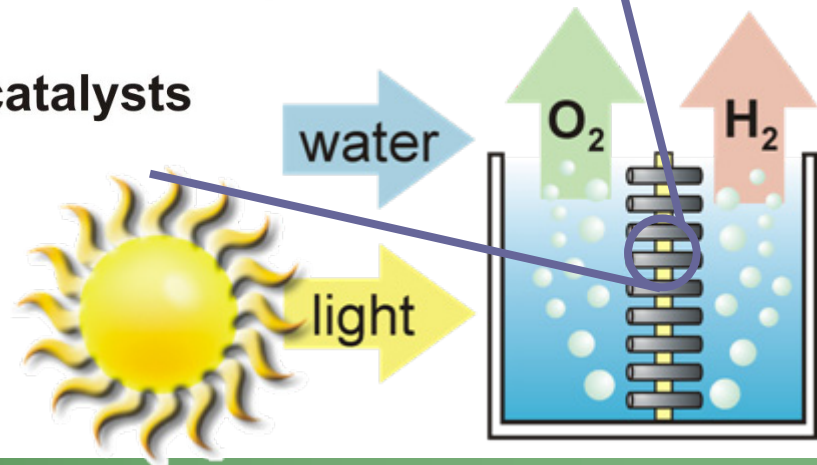


Integrated architecture

UNIVERSITY



Details to follow!!!



Walter, M.; Warren, E.; McKone, J.; Boettcher, S. W.; Qixi, M.; Santori, L.; Lewis, N. S. Solar Water Splitting Cells. *Chem. Rev.* **2010**, *110*, 6446-6473.



Overview

PART 1:

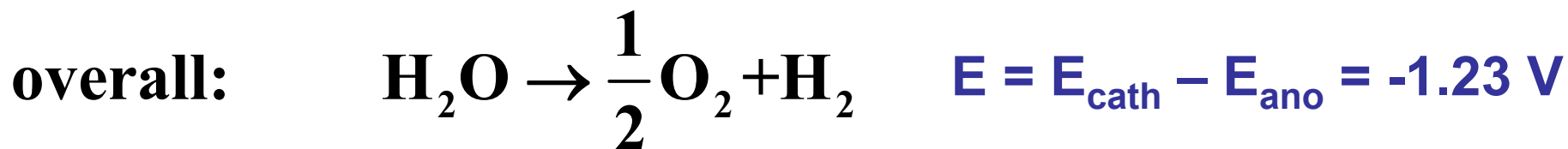
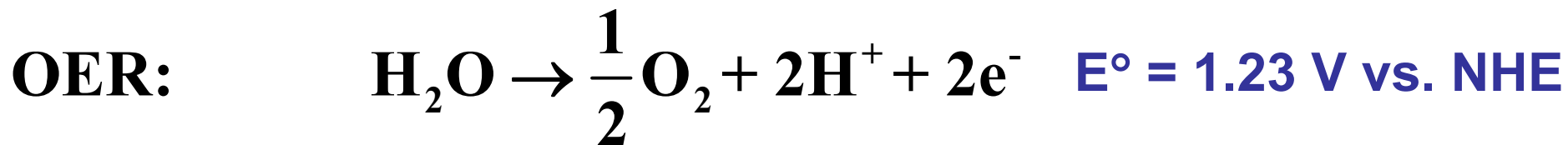
- **Thermodynamics and Electrochemical Reactions**
- **Semiconductors Physics**
- **Liquid junctions and Photoelectrochemistry (PEC)**

PART 2:

- **Electrocatalysis and Electrochemical Kinetics**
- **Integrated devices and Literature examples**



Thermodynamics



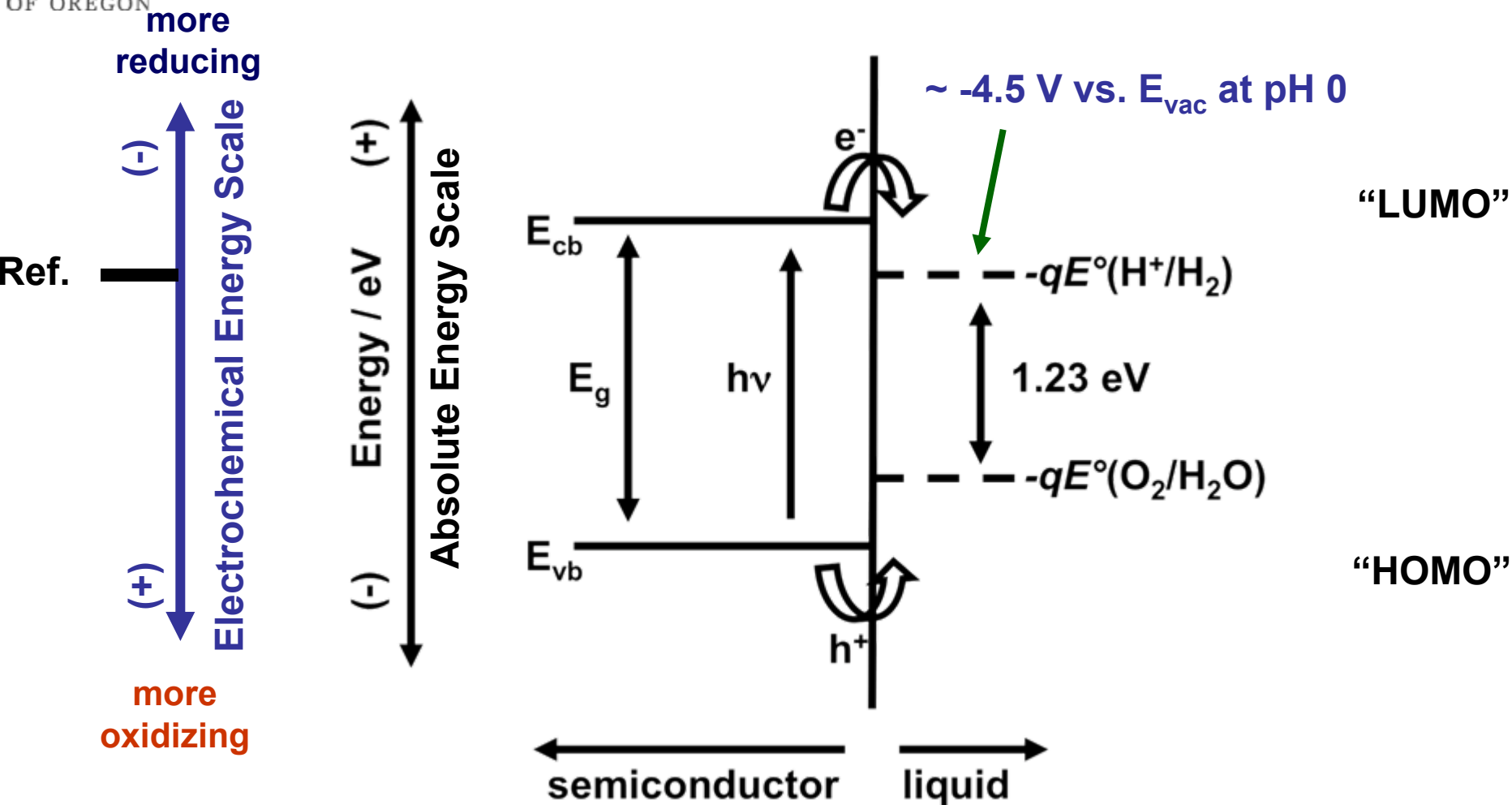
$$\Delta G = -nFE = 237 \text{ kJ mol}^{-1}$$

Oxygen evolution reaction (OER) and hydrogen evolution reaction (HER) for overall water splitting

Walter, M.; Warren, E.; McKone, J.; Boettcher, S. W.; Qixi, M.; Santori, L.; Lewis, N. S. Solar Water Splitting Cells. *Chem. Rev.* **2010**, *110*, 6446-6473.



(Over-)Simplified Picture



Basic Idea: **(a)** Semiconductor separates photoexcited electron-hole pairs. **(b)** e^- reduce H^+ to make H_2 **(c)** h^+ oxidizes water to make O_2



Review of Oxidation/Reduction

$$\Delta G^\circ = -RT \ln K$$

$$\Delta G = \Delta G^\circ + RT \ln Q \quad \Delta G = -nFE$$

$$E = E^\circ - \frac{RT}{nF} \ln \frac{a_{\text{Red}}}{a_{\text{Ox}}} \quad \text{Nernst Equation}$$

$$E_{\text{HER}} = E^\circ_{\text{HER}} - \frac{RT}{2F} \ln \frac{P_{\text{H}_2}}{[\text{H}^+]^2}$$

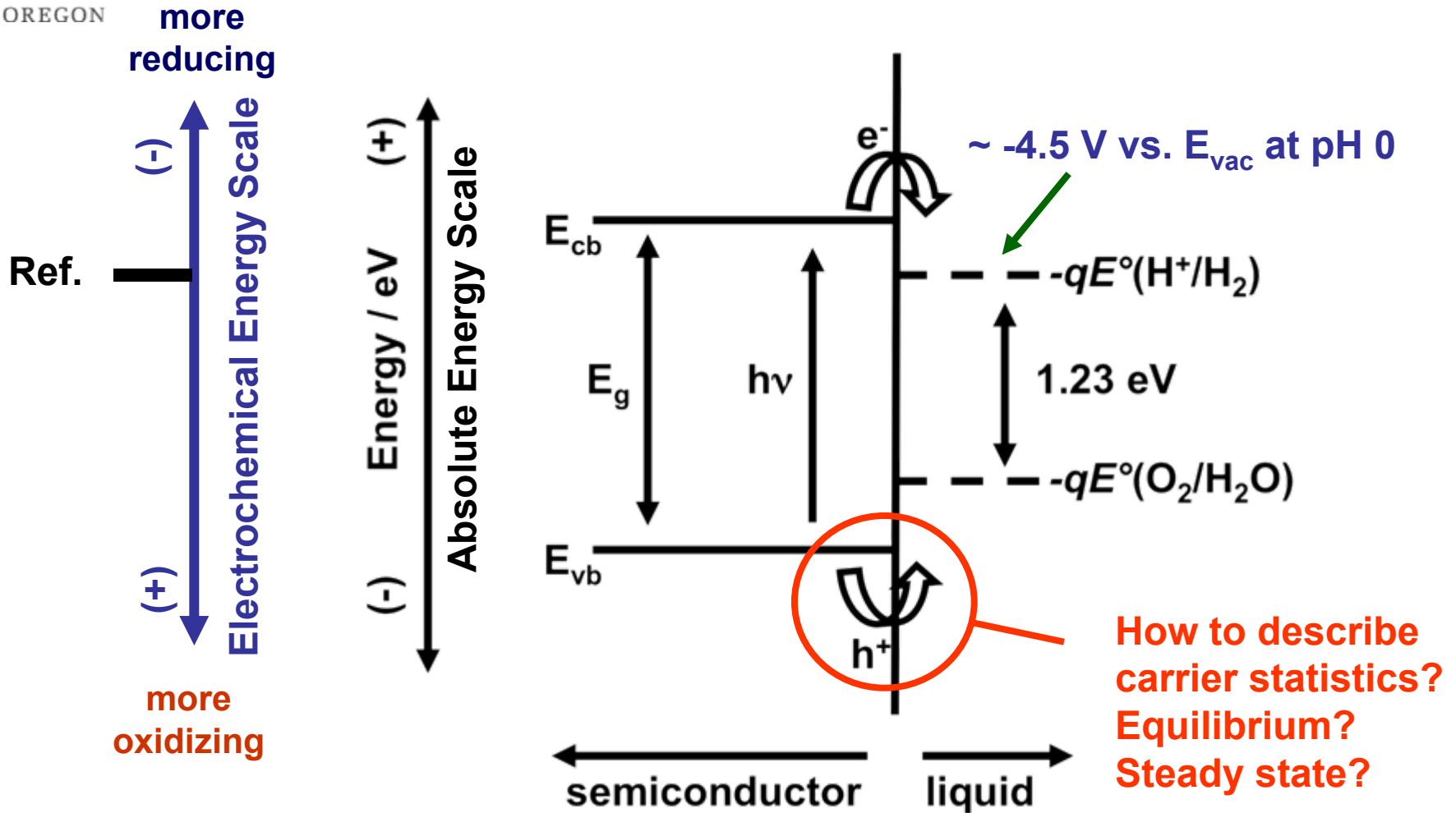
$$E_{\text{OER}} = E^\circ_{\text{OER}} - \frac{RT}{2F} \ln \frac{1}{[\text{H}^+]^2 (P_{\text{O}_2})^{1/2}}$$

Both HER and OER are pH dependent.

The total potential needed, $E_{\text{OER}} - E_{\text{HER}} = 1.23 \text{ V}$, is not.



(Over-)Simplified Picture

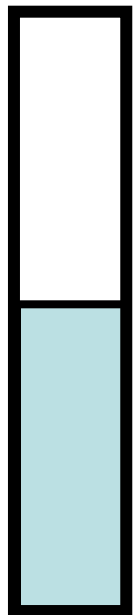


Basic Idea: (a) Semiconductor separates photoexcited electron-hole pairs. (b) e^- reduce H^+ to make H_2 (c) h^+ oxidizes water to make O_2



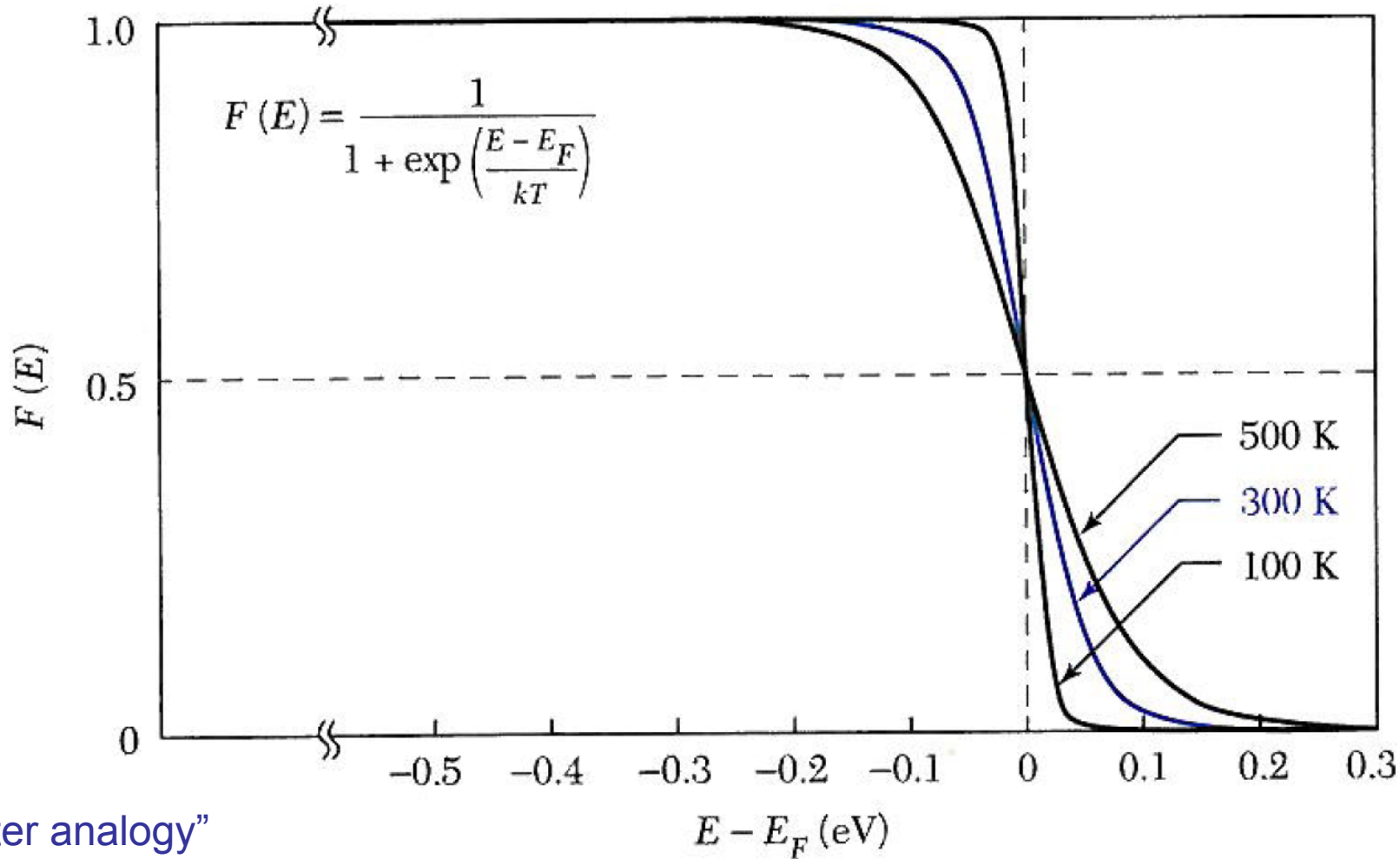
Fermi Levels Describe Energy of Carriers

UNIVERSITY OF OREGON



DOS

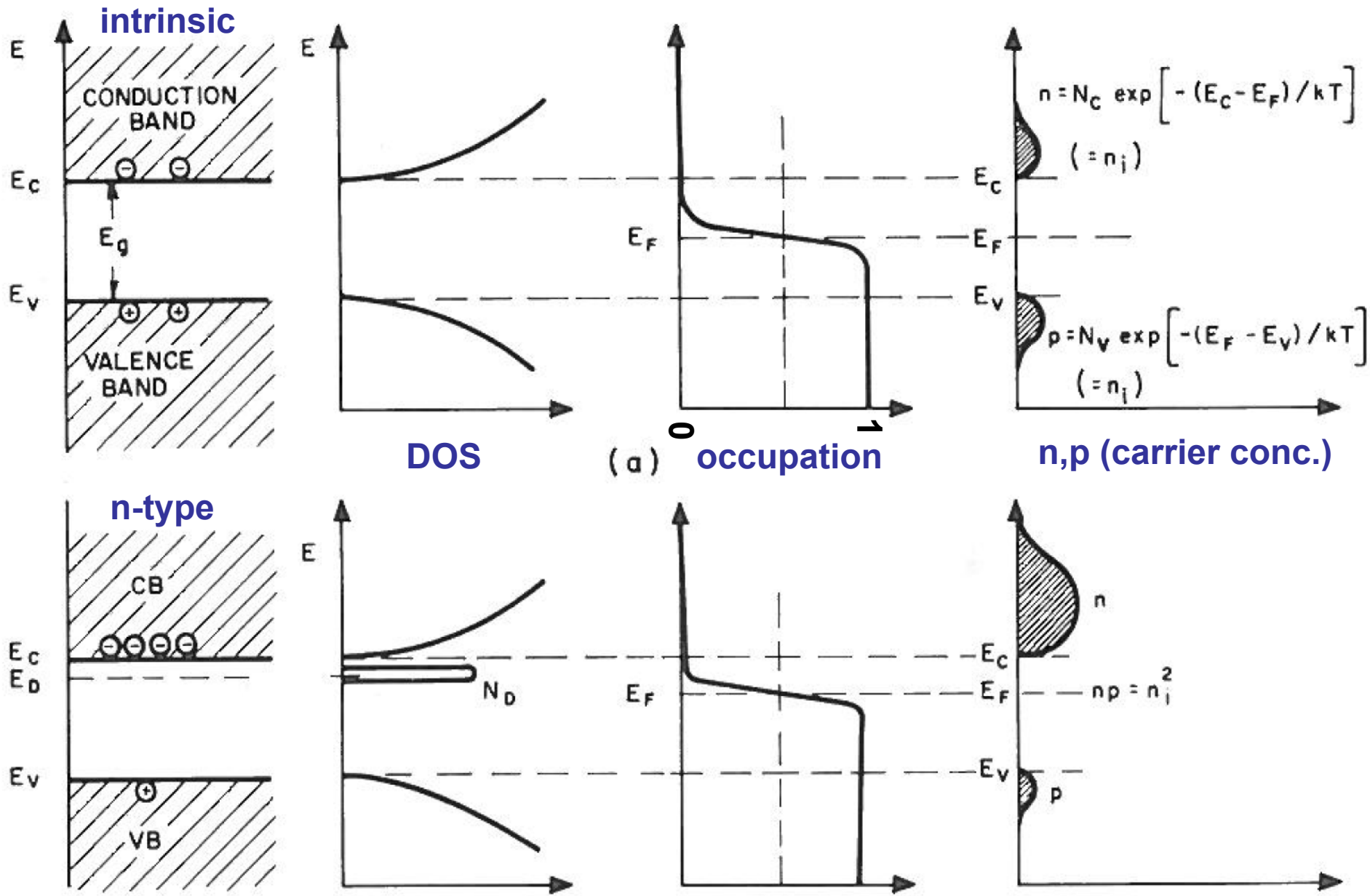
energy



“glass of water analogy”

Sze, S. M.; Kwok, K. N. *Physics of Semiconductor Devices*, 2007.

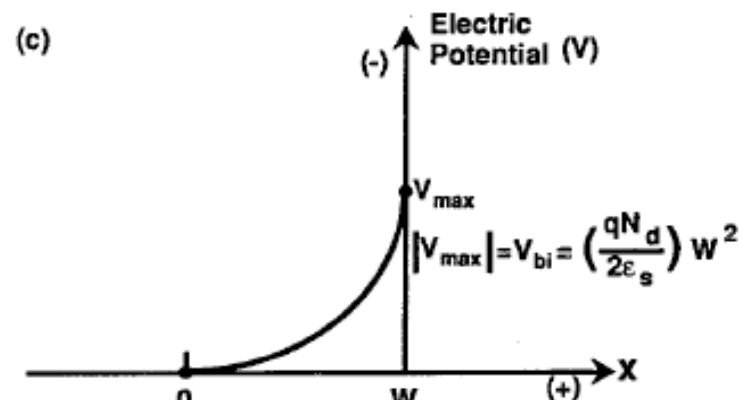
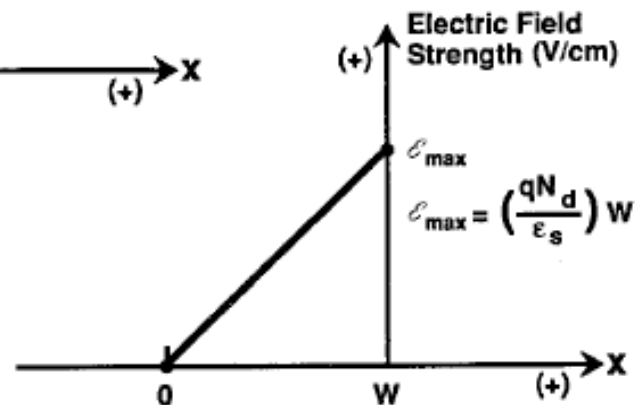
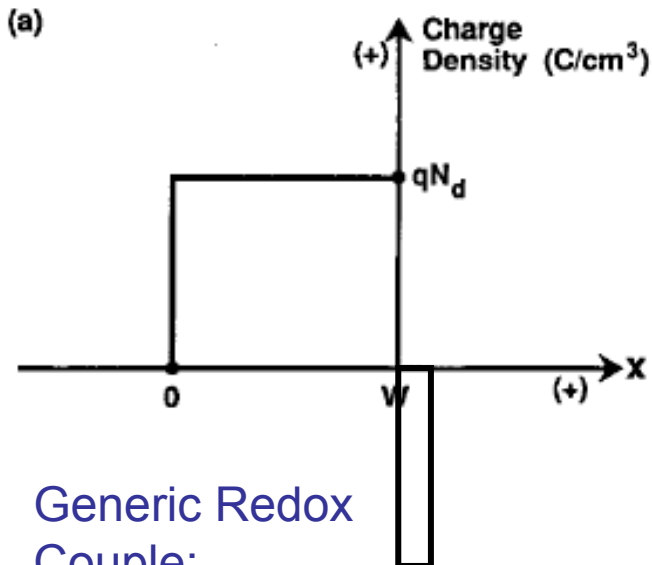
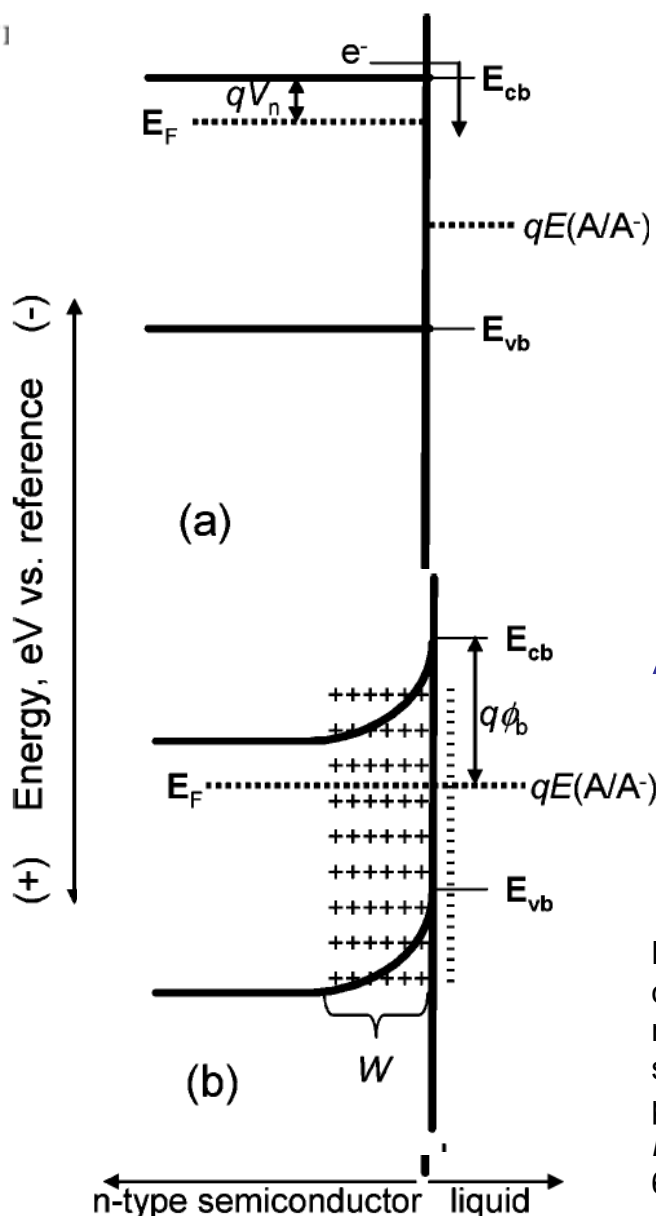
O Semiconductor Properties and Doping



Sze, S. M.; Kwok, K. N. *Physics of Semiconductor Devices*, 2007.

Equilibration with Solution Redox Couples

UNI
OF



Lewis, N. S. Chemical control of charge transfer and recombination at semiconductor photoelectrode surfaces. *Inorg. Chem.* **2005**, *44*, 6900-6911.



Dark Current-Voltage Behavior

Electron transfer at semiconductor-liquid interfaces is "simple" kinetics:

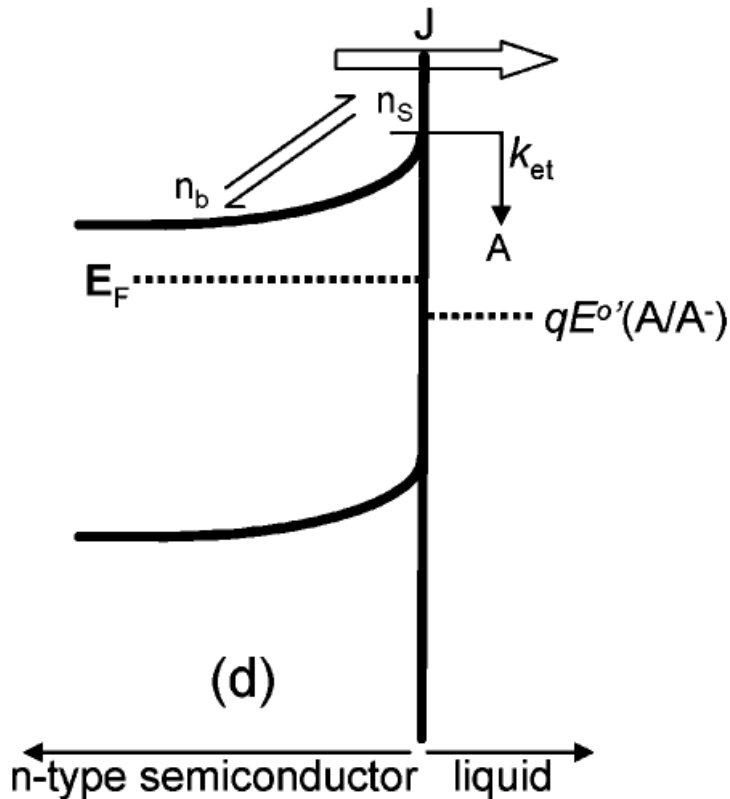
$$J_{et,f}(E) = -qk_{et,f}[A]n_s$$

$$J_{et,r}(E) = -qk_{et,r}[A^-]$$

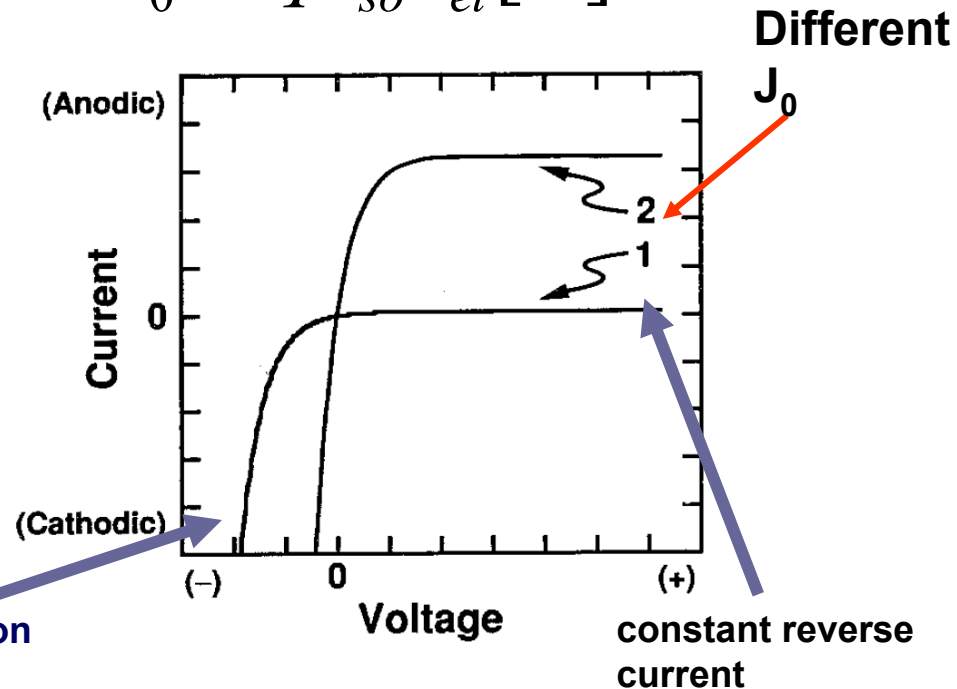
$$n_s = N_d e^{q(E_{fb} - E)/k_B T}$$

$$J_{et} = J_0 \left[e^{qV/k_B T} - 1 \right]$$

$$J_0 = qn_{so}k_{et}[A]$$



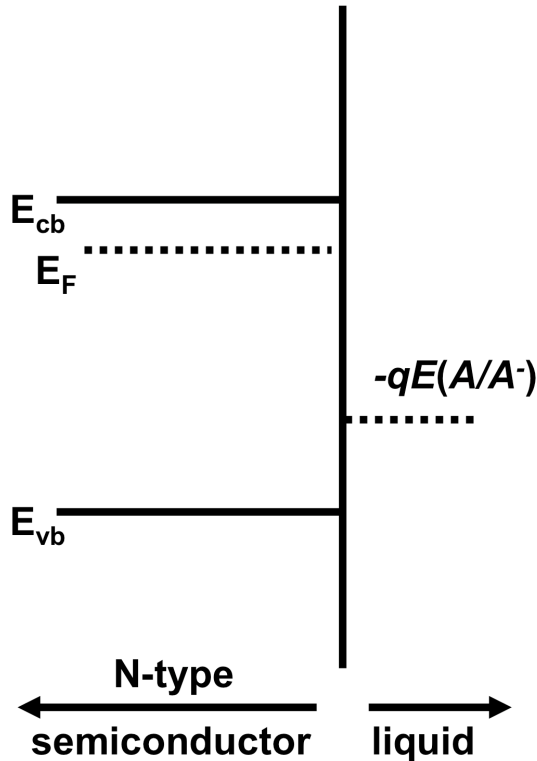
exponential turn-on in forward bias



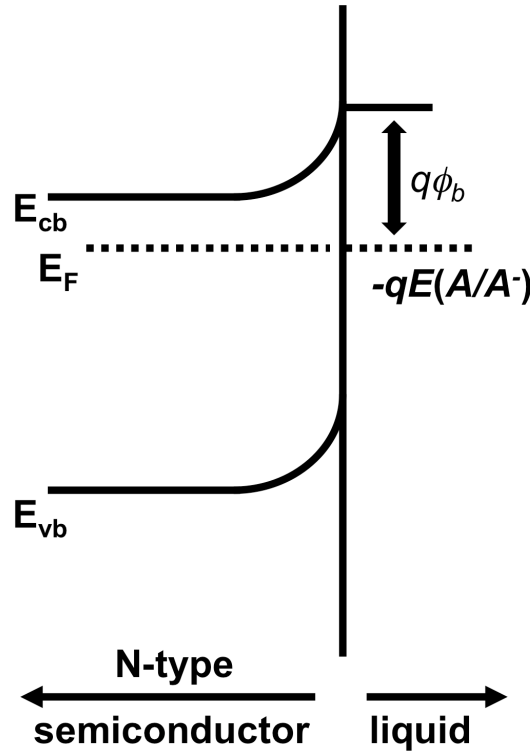


Semiconductor-solution contacts under illumination

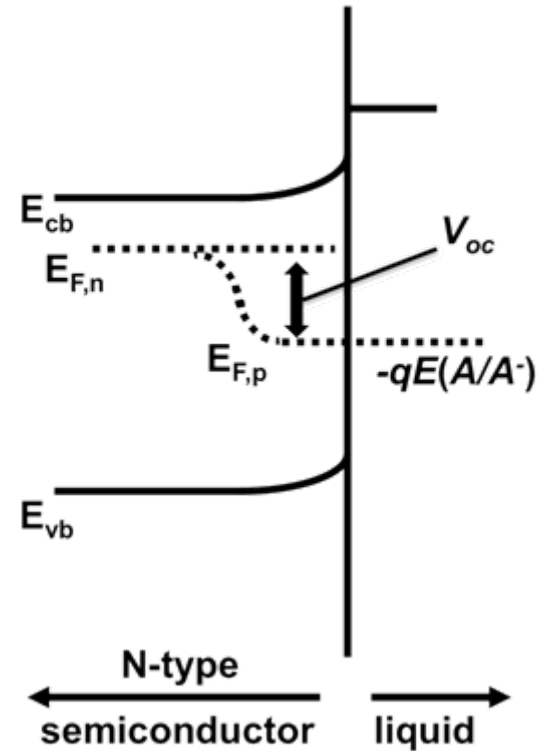
A. before equilibrium



B. after equilibrium



C. illuminated

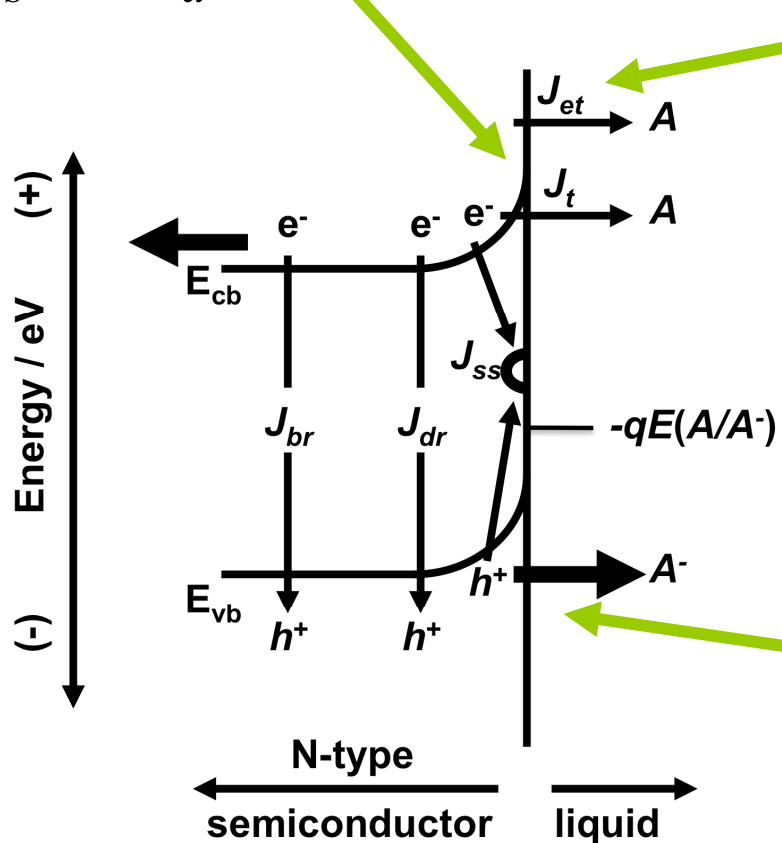


bands unbend; new quasi-equilibrium with different e- and h+ conc.



The measured current and voltage depends on the rates of fundamental processes

$$n_s = N_d e^{q(E_{fb} - E)/k_B T}$$



$$J_{et} = -qk_{et}[A]n_s$$

$$V_{oc} = \frac{nk_B T}{q} \ln \left(\frac{J_{ph}}{J_0} \right)$$

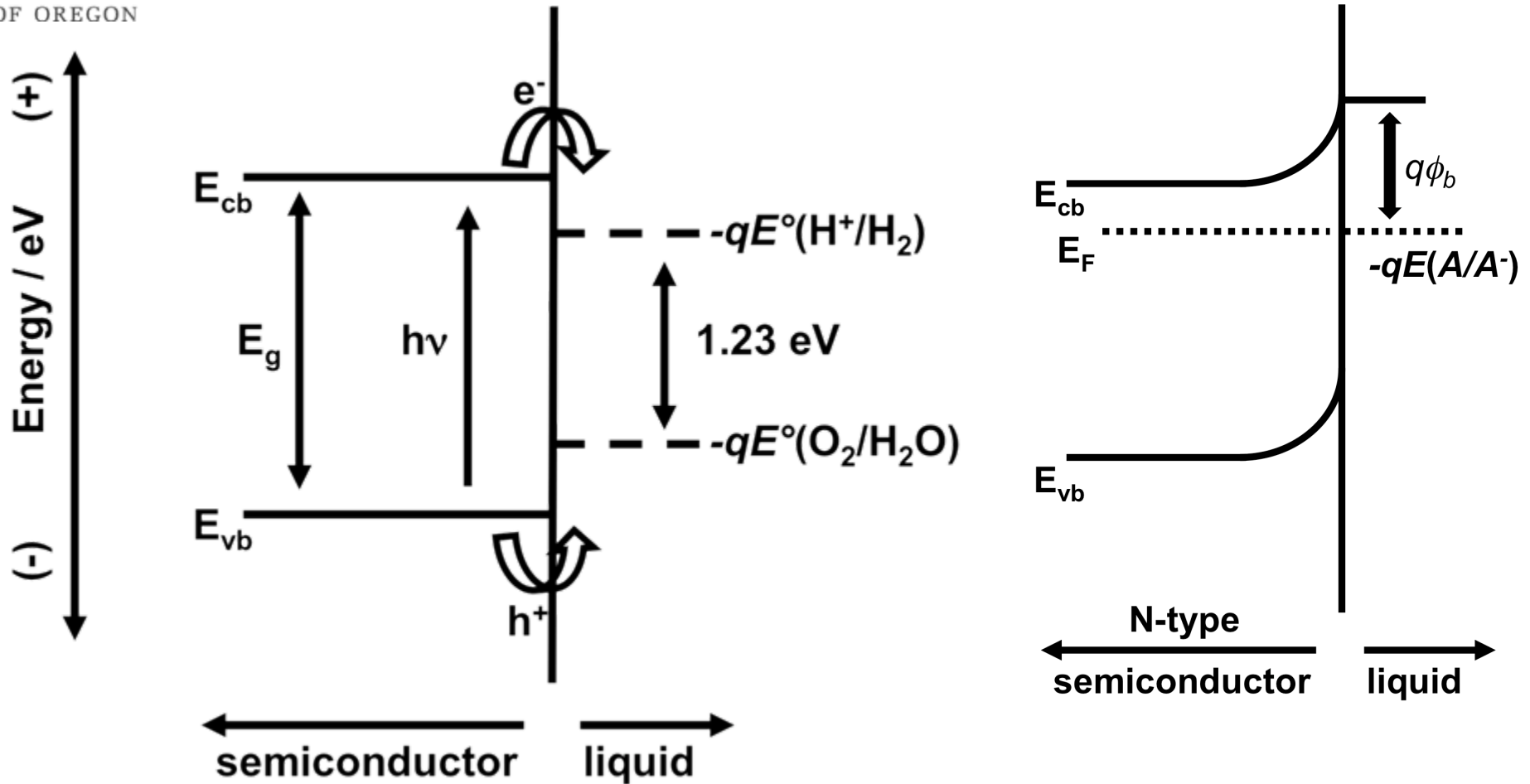
$$J_{ph} = \Phi \Gamma$$

photon flux times collection efficiency



“Flat Band” potential and absolute energy levels

UNIVERSITY OF OREGON

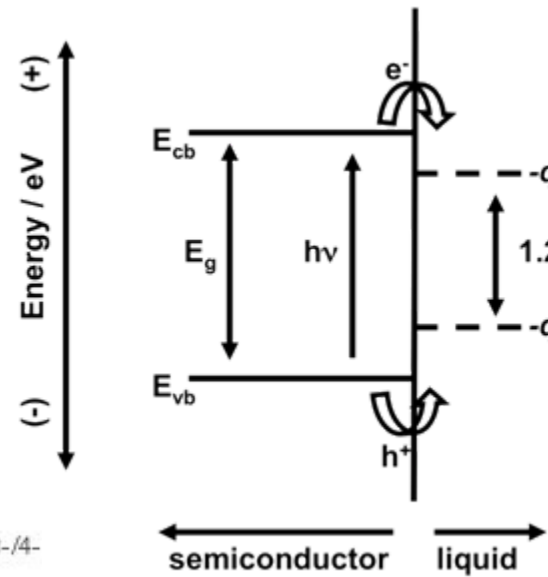
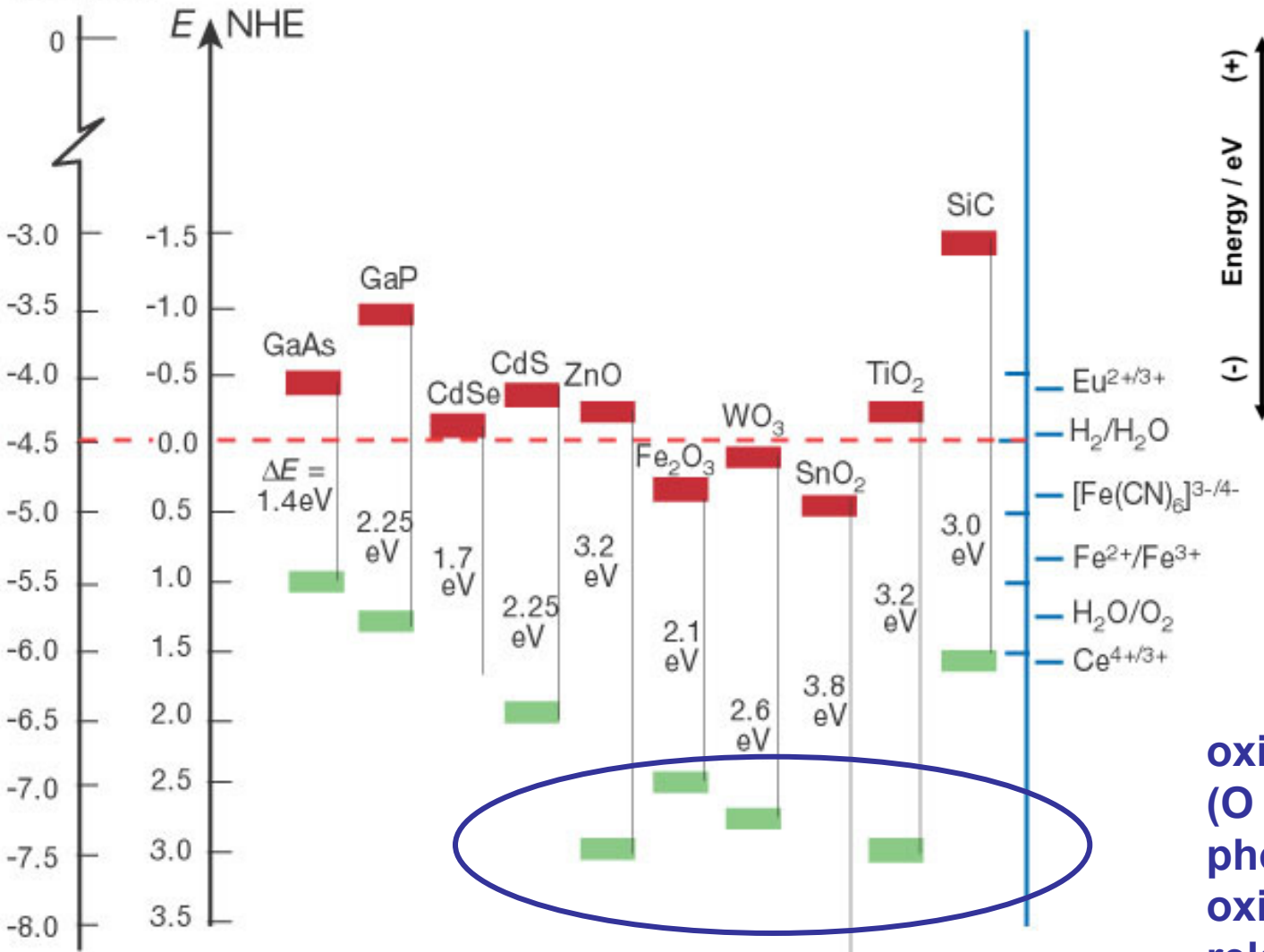


What determines the equilibrium barrier height ϕ_b ?

What semiconductors can split water based on thermodynamics?

Absolute band-edge positions

Vacuum



oxide VB low,
(O 2p states stable)
photovoltage from
oxide anodes small
relative to band-gap

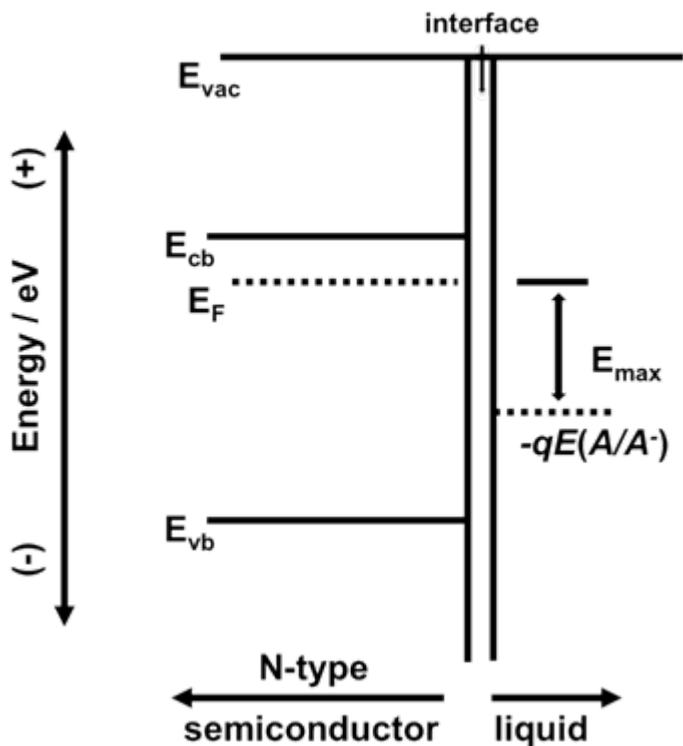
Gratzel, M. Photoelectrochemical cells. *Nature* **2001**, 414, 338-344.
 Bak, T.; Nowotny, J.; Rekas, M.; Sorrell, C. C. Photo-electrochemical hydrogen generation from water using solar energy. Materials-related aspects. *Int. J. Hydrogen Energy* **2002**, 27, 991-1022.



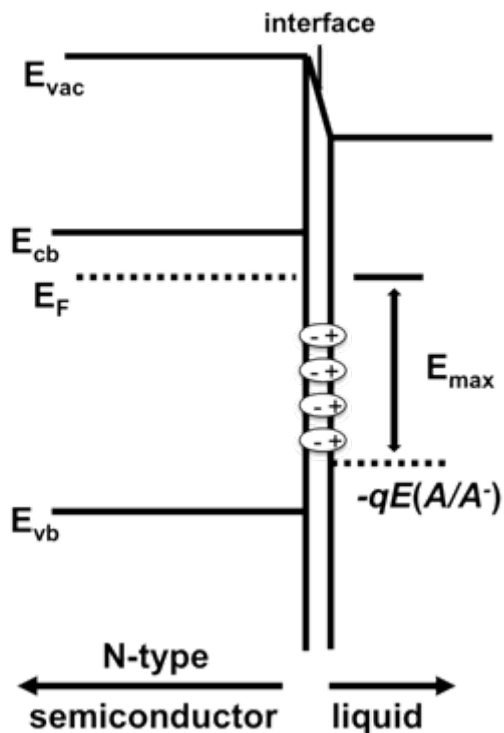
Band-edges move via surface dipoles

UNIVERSITY OF OREGON

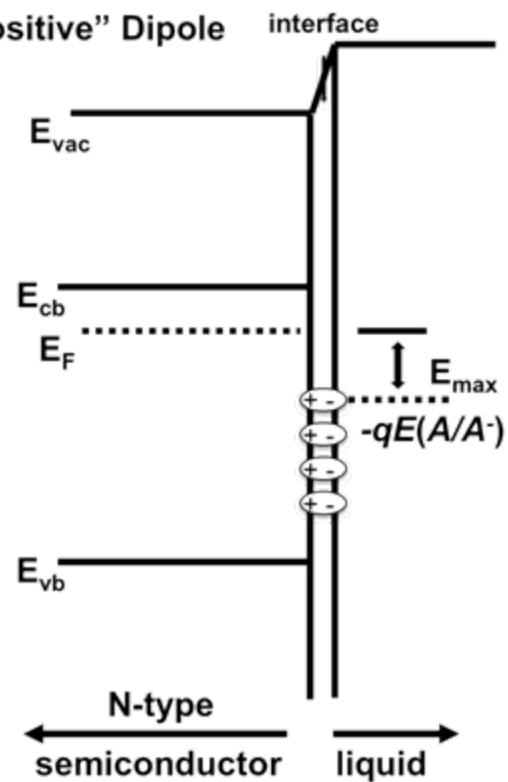
A. Bare Interface



B. "Negative" Dipole



C. "Positive" Dipole

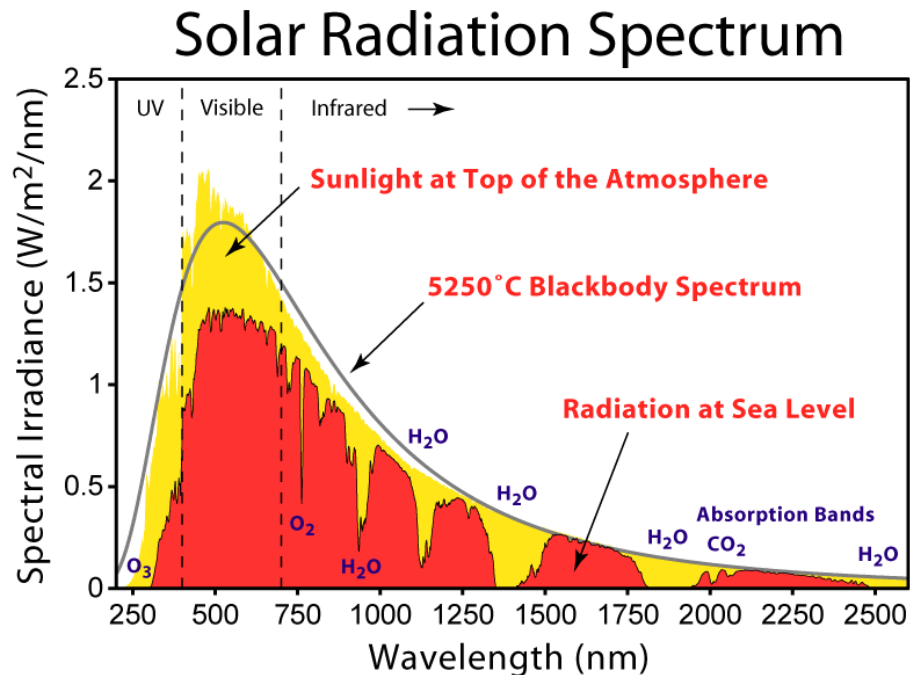
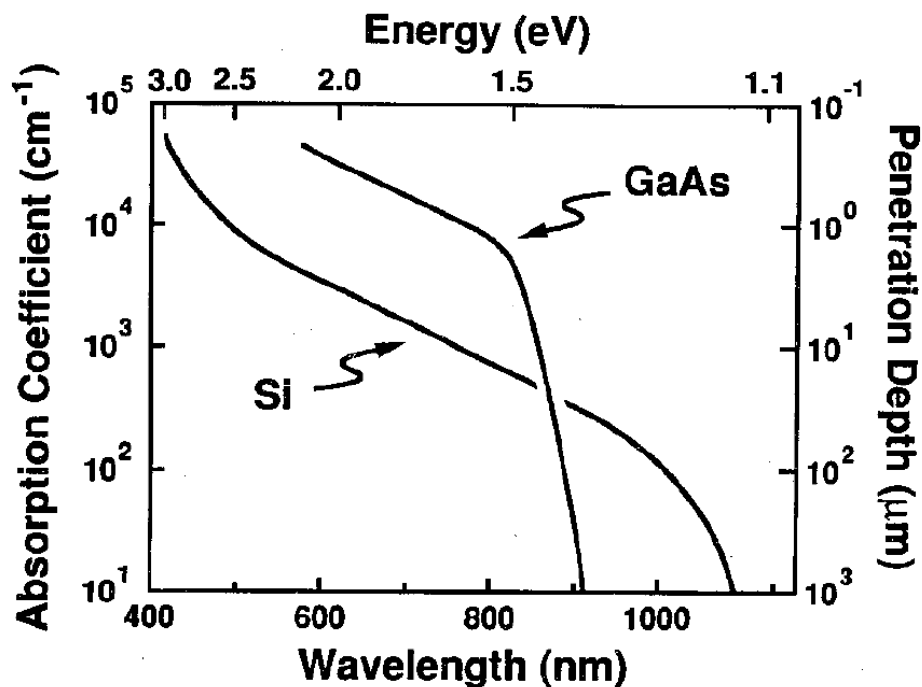


Surface dipoles are the result of: absorbed ions, protonated/deprotonated surface hydroxyls, surface termination, charged surface states, etc.



Semiconductors: Light Absorption

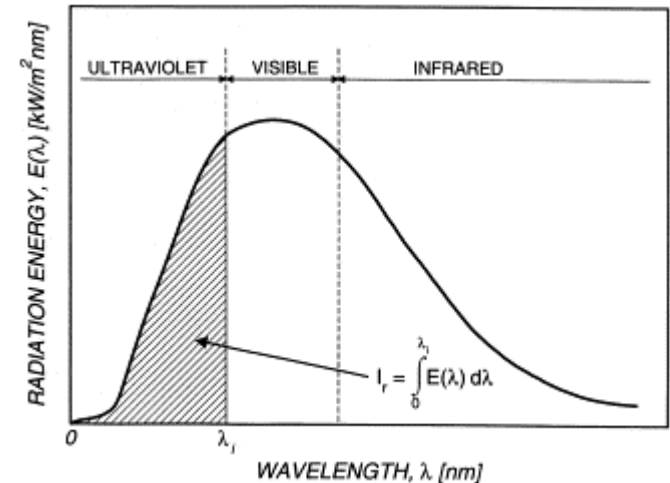
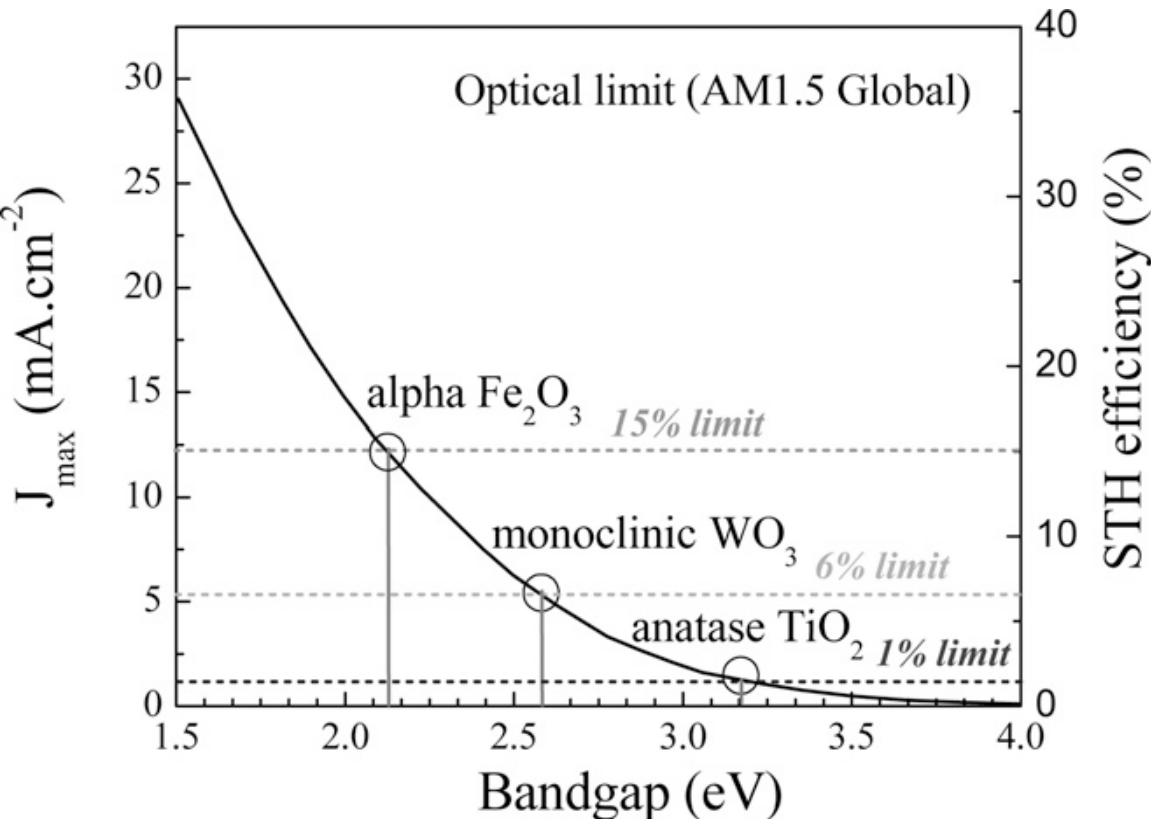
UNIVERSITY
OF OREGON



wikipedia

Tan, M. X.; Laibinis, P. E.; Nguyen, S. T.; Kesselman, J. M.; Stanton, C. E.; Lewis, N. S. Principles and application of semiconductor photoelectrochemistry. *Progress in Inorganic Chemistry*, Vol 41 1994, 41, 21-144.

Semiconductors: Light Absorption

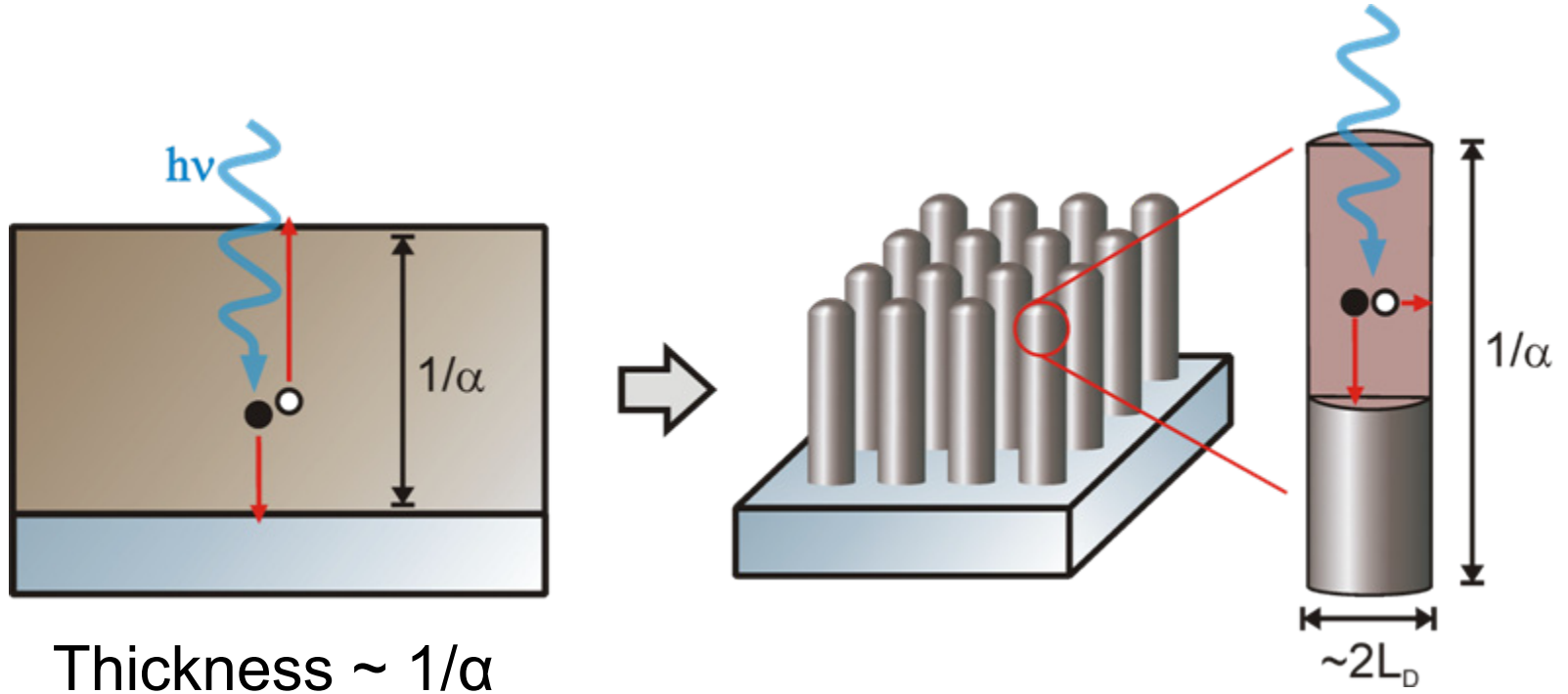


Research challenge:
Design low-cost stable materials (oxides?) with smaller band-gaps?
How do we make stabilize conventional semiconductors?

Chen, Z. B.; et. al. Accelerating materials development for photoelectrochemical hydrogen production: Standards for methods, definitions, and reporting protocols. *J. Mater. Res.* **2010**, *25*, 3-16.

Bak, T.; Nowotny, J.; Rekas, M.; Sorrell, C. C. Photo-electrochemical hydrogen generation from water using solar energy. Materials-related aspects. *Int. J. Hydrogen Energy* **2002**, *27*, 991-1022.

Semiconductors: Carrier Collection



Thickness $\sim 1/\alpha$

$$L_D = \sqrt{D \cdot \tau} \quad D = \frac{\mu \cdot k_B \cdot T}{q}$$

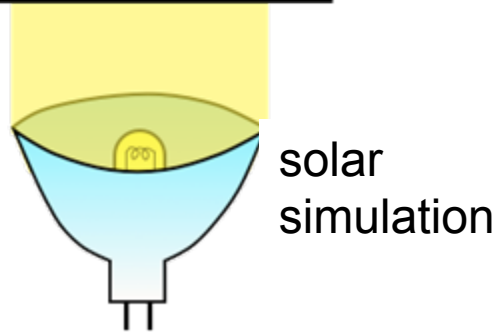
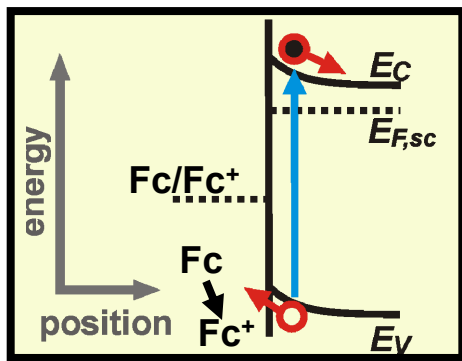
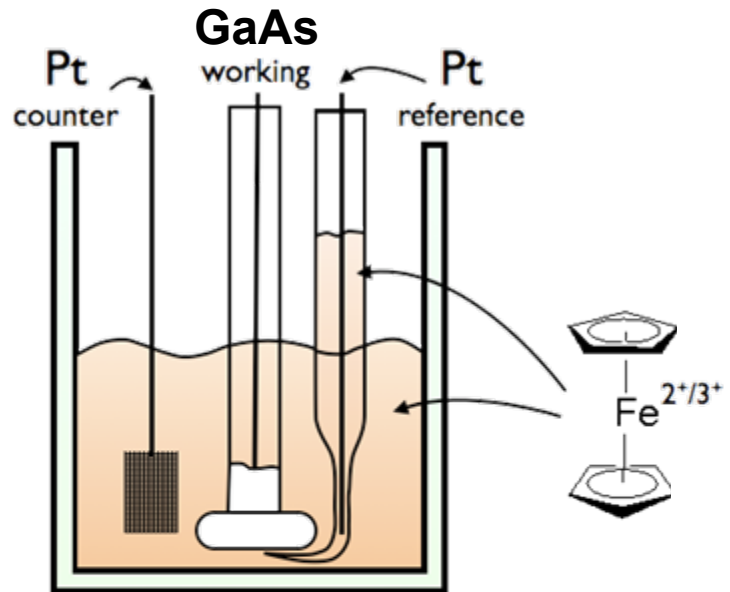
Three dimensional geometry can enhance carrier collection... but at a price.

Comparison of the device physics principles of planar and radial p-n junction nanorod solar cells
 B. M. Kayes, H. A. Atwater and N. S. Lewis *Journal of Applied Physics*, 2005, 97,

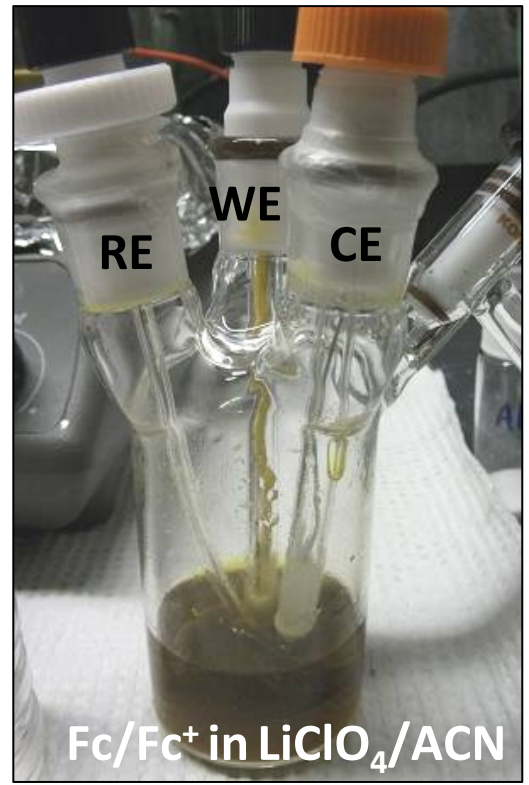
Non-aqueous photoelectrochemistry is a tool to characterize semiconductors for PEC



GaAs electrodes



solar simulation

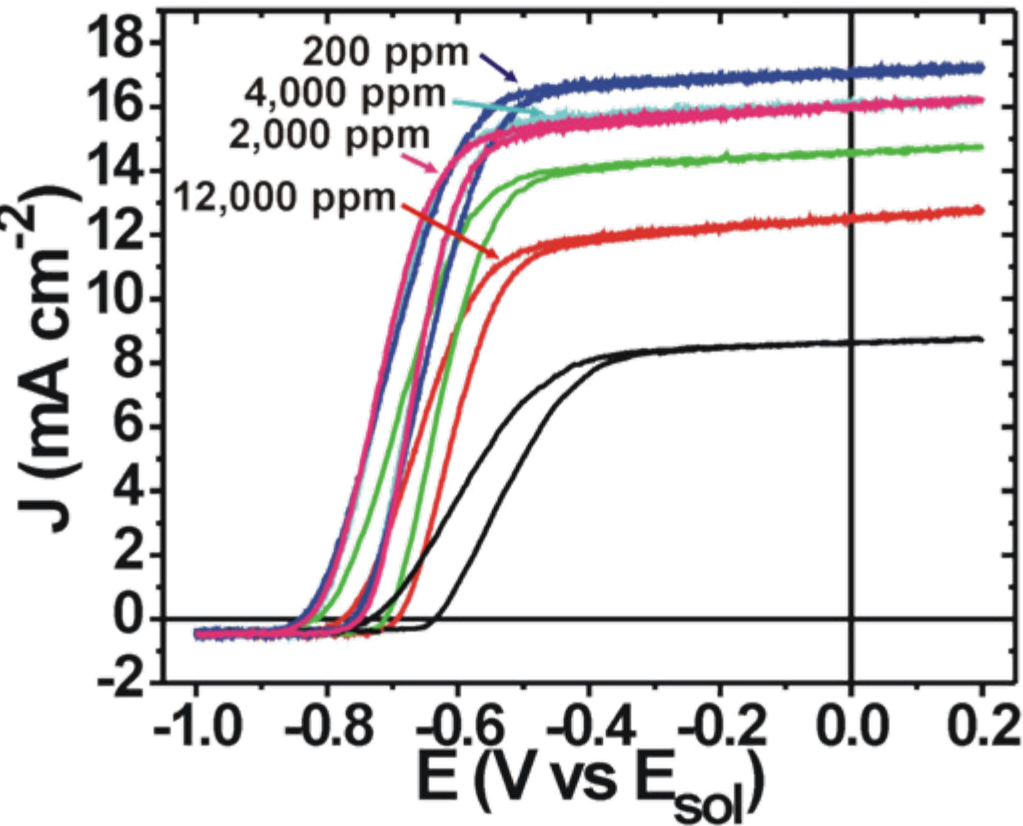


reversible redox couple with fast kinetics

Gronet, C. M.; *Appl. Phys. Lett.* **43**, 1, 115-117

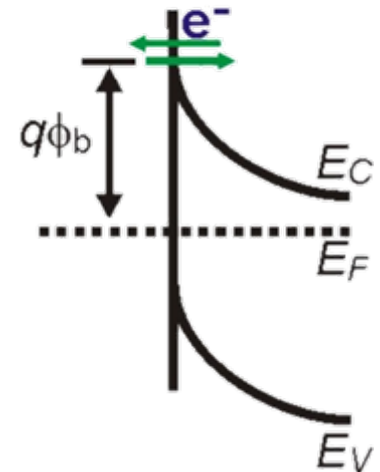


Example: PEC J - E on n-GaAs

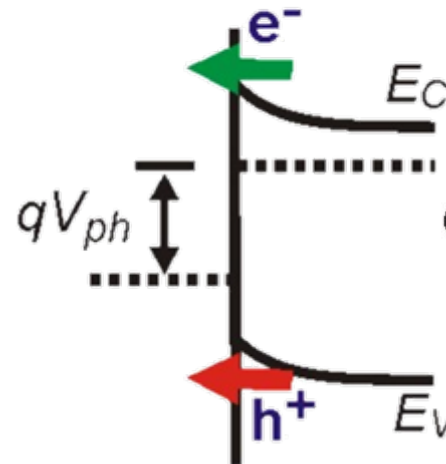


(low ff is due to solution resistance, $\sim 100 \Omega$, quantitative correction yield $\eta > 11 \%$)

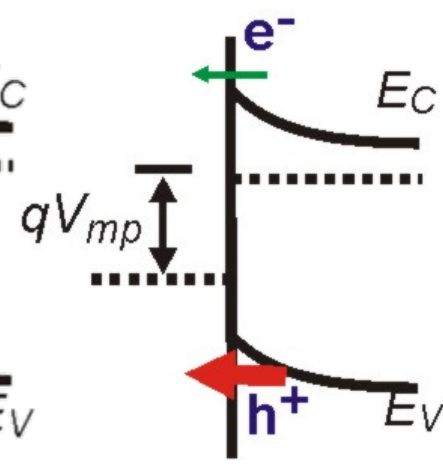
equilibrium, dark



open circuit, illuminated

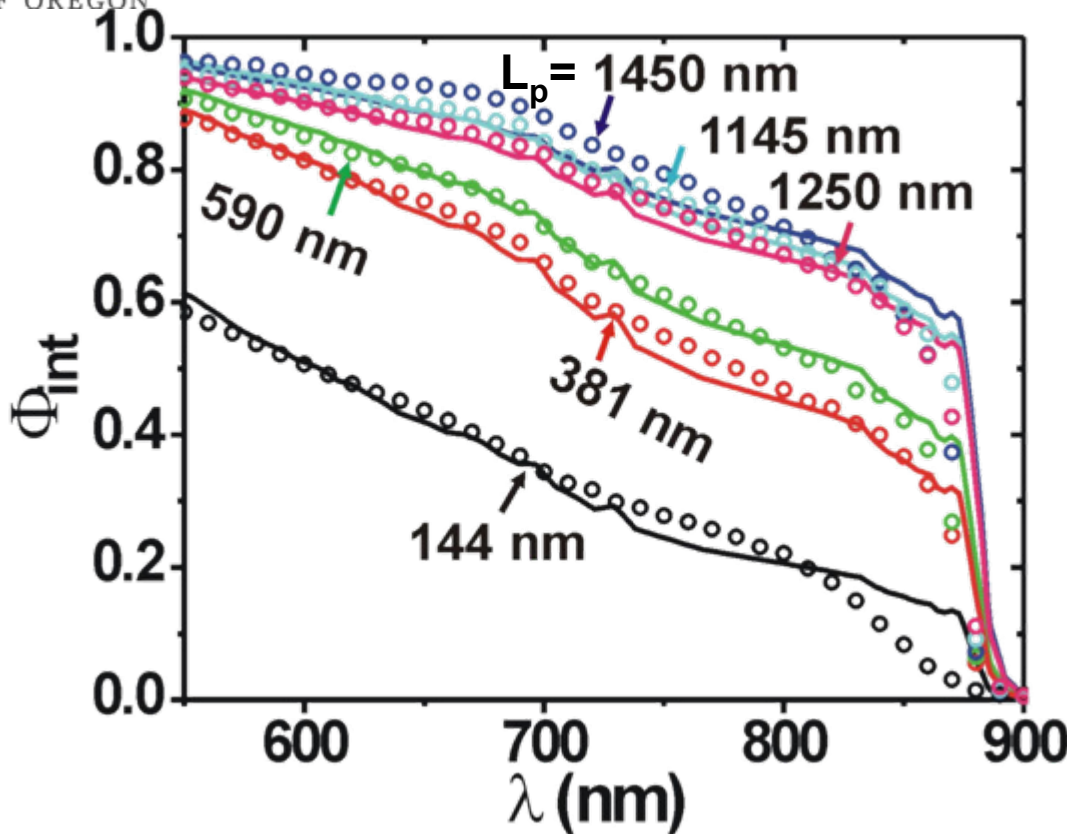


steady-state, illuminated





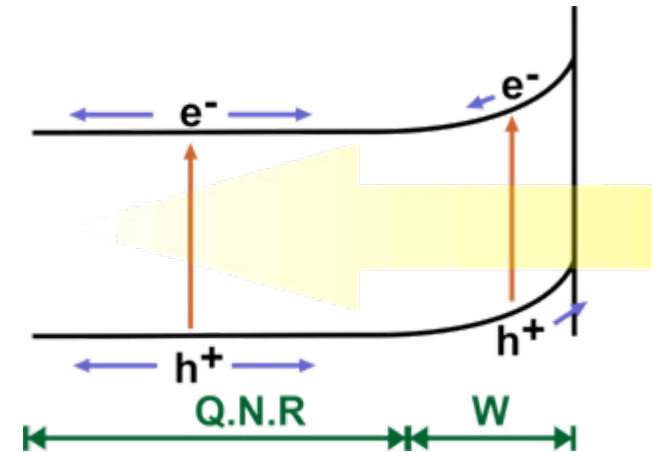
Diffusion length determination from quantum efficiency



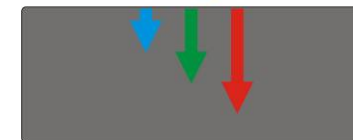
~1.5 μ m diffusion length sufficient to design high efficiency PV or PEC device.
 What defects are present? How can we eliminate them to improve response?

Gärtner Model:

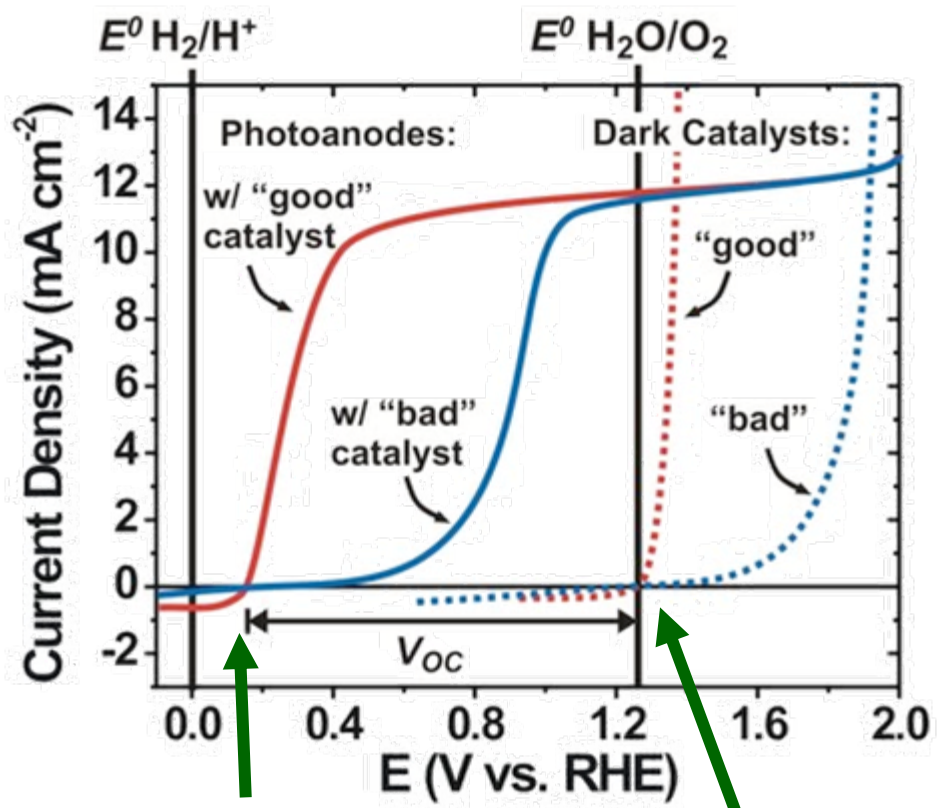
$$\phi_{int} = 1 - \frac{e^{-\alpha(\lambda)W}}{1 + \alpha(\lambda)L_p}$$



$R \sim 25\%$

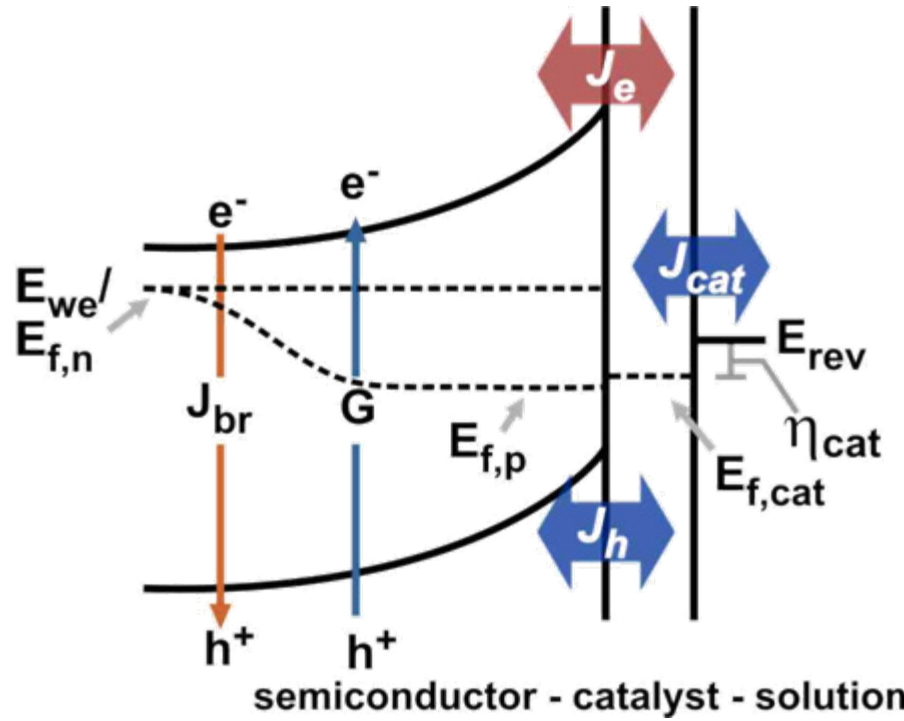


PART 2: Surface Electrocatalysis and Integrated Architectures

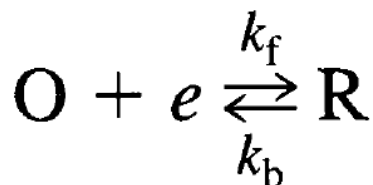


catalyst photoactive semiconductor

catalyst on metal electrode (no photoactivity)

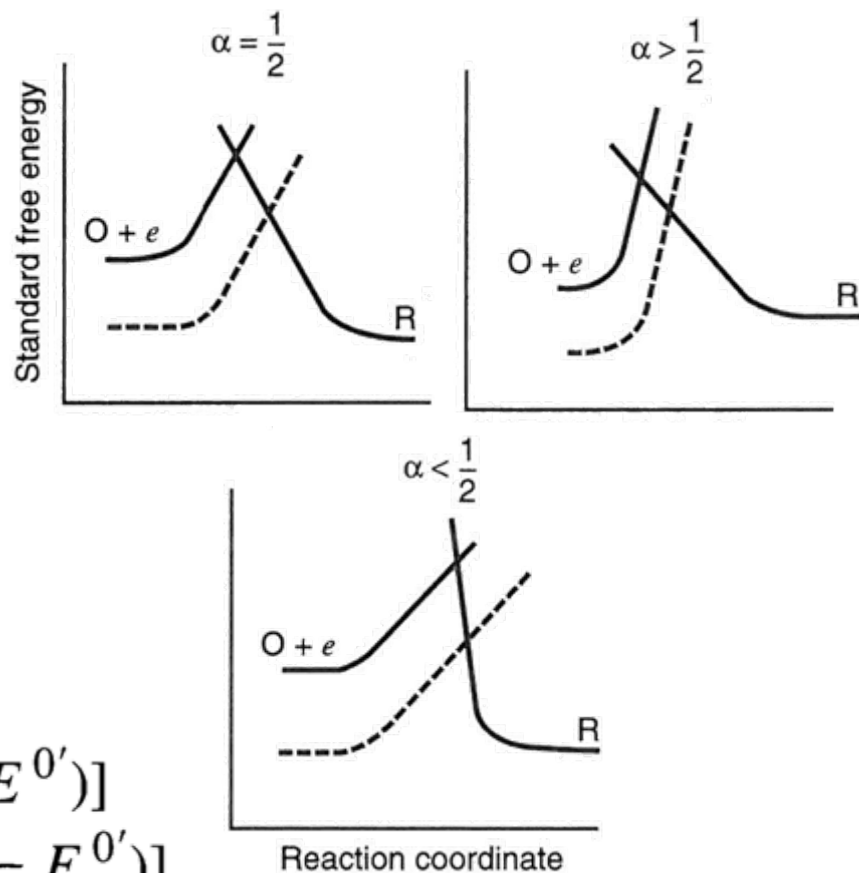
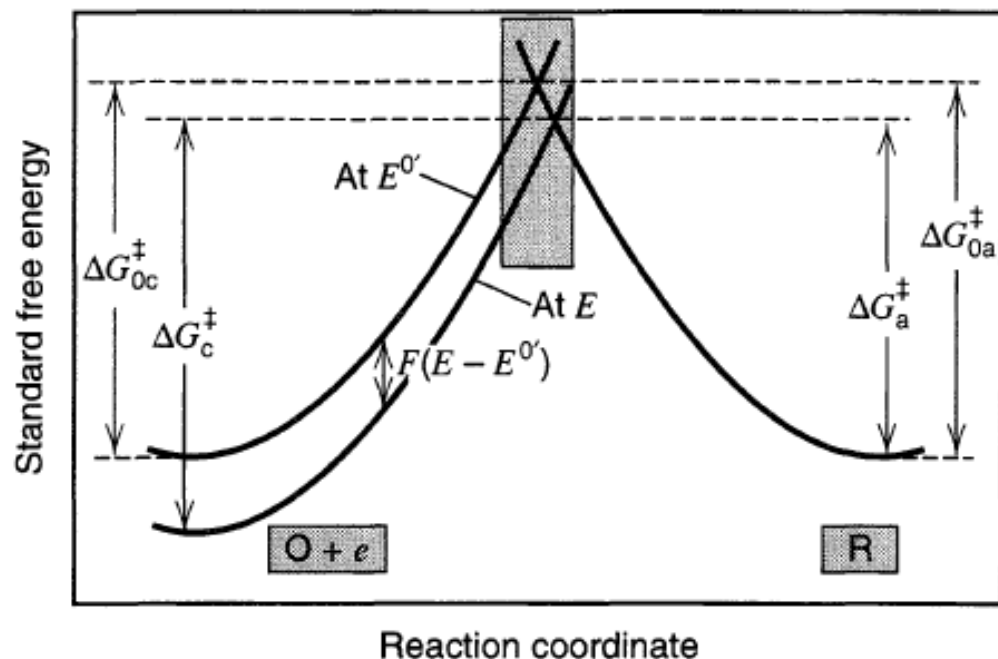


Electrochemical Reaction Kinetics



$$k_f = A_f \exp(-\Delta G_c^\ddagger / RT)$$

$$k_b = A_b \exp(-\Delta G_a^\ddagger / RT)$$



$$k_f = A_f \exp(-\Delta G_{0c}^\ddagger / RT) \exp[-\alpha f(E - E^{0'})]$$

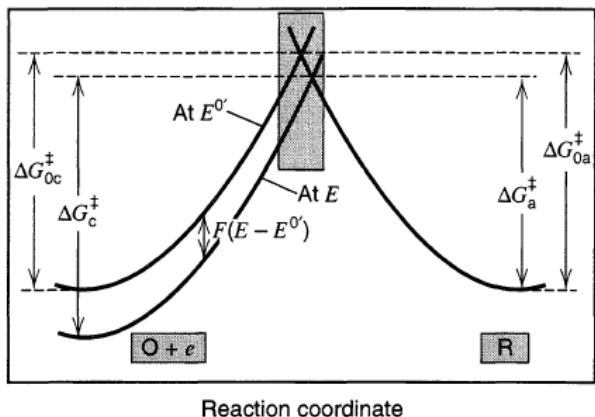
$$k_b = A_b \exp(-\Delta G_{0a}^\ddagger / RT) \exp[(1 - \alpha) f(E - E^{0'})]$$

Bard, A. J.; Faulkner, L. R. *Electrochemical Methods: Fundamentals and Applications*; Wiley, 2000.



Electrochemical Reaction Kinetics

UNIVERSITY OF OREGON



Butler-Volmer Expression for a single electron-transfer step:

$$i = i_0 \left[\frac{C_O(0, t)}{C_O^*} e^{-\alpha f \eta} - \frac{C_R(0, t)}{C_R^*} e^{(1-\alpha) f \eta} \right]$$

$$i_0 = F A k^0 C_O^{*(1-\alpha)} C_R^{*\alpha}$$

Exchange Current Density

α describes the shape of the potential barrier and is normally taken as 0.5. ($f = F/RT$)

$$i = i_0 \left[e^{-\alpha f \eta} - e^{(1-\alpha) f \eta} \right]$$

assume fast mass transport

$$\eta = a + b \log i \quad a = \frac{2.3RT}{\alpha F} \log i_0 \quad b = \frac{-2.3RT}{\alpha F}$$

Ignore Reverse Reaction = Tafel Eqn. for Electrode Kinetics

Bard, A. J.; Faulkner, L. R. *Electrochemical Methods: Fundamentals and Applications*; Wiley, 2000.

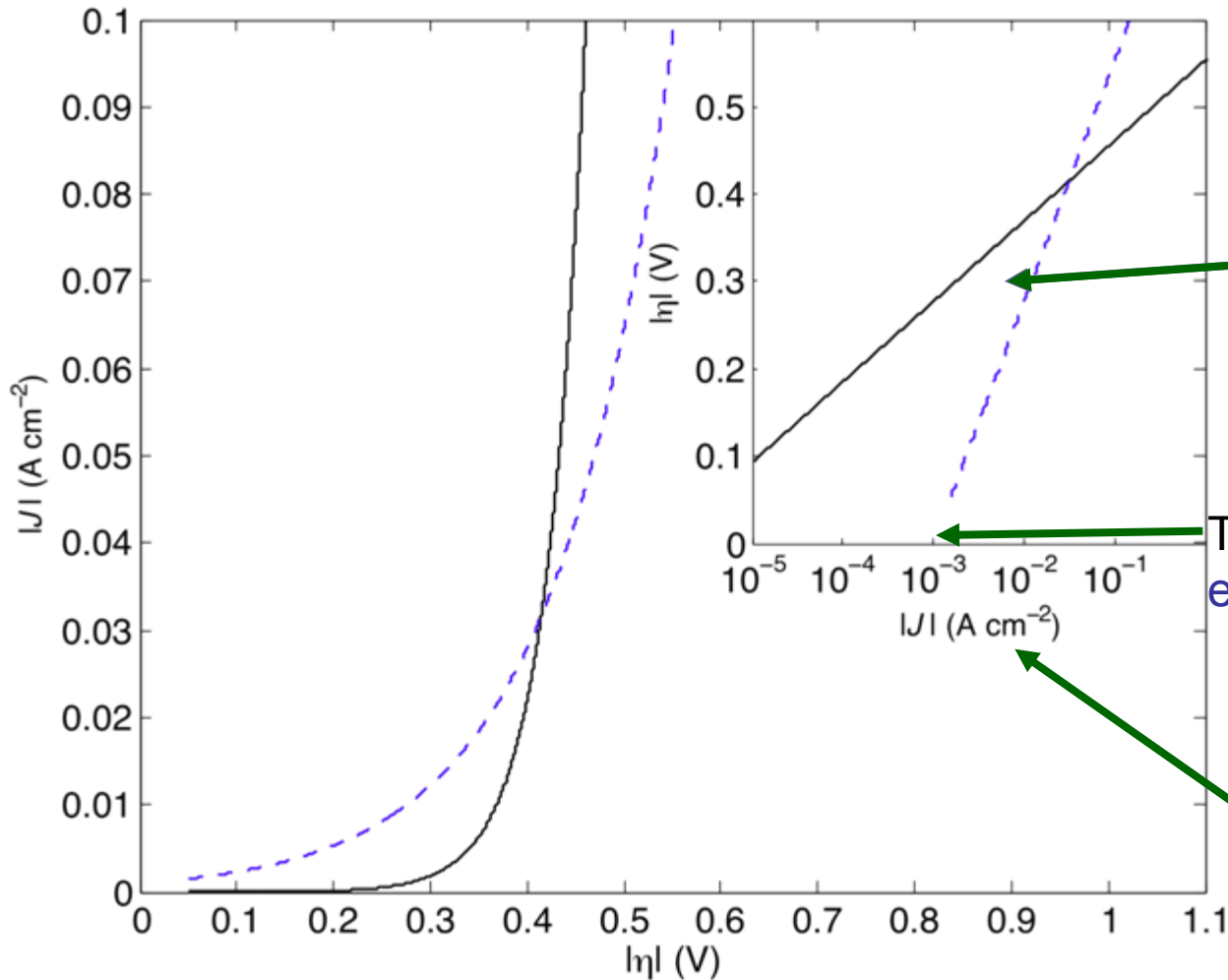


Tafel Slope and Exchange Current

$$\eta = a + b \log i$$

$$a = \frac{2.3RT}{\alpha F} \log i_0$$

$$b = \frac{-2.3RT}{\alpha F}$$



Tafel slope = $b = 60 \text{ mV} / \alpha$
only for 1 e⁻ reaction

Tafel (x)-intercept = $-a/b = \log i_0$
eq. "exchange-current"

convention to plot
I on the y-axis!



Multistep reactions

Example:



* Indicates bonded to the surface

For multi-step $n e^-$ reaction:

$$i = i_0 [e^{-(n'+\alpha)f\eta} - e^{(n''+1-\alpha)f\eta}]$$

$$n = n' + n'' + 1$$

$$\text{Tafel slope} = b = 60 \text{ mV} / (n'+\alpha)$$

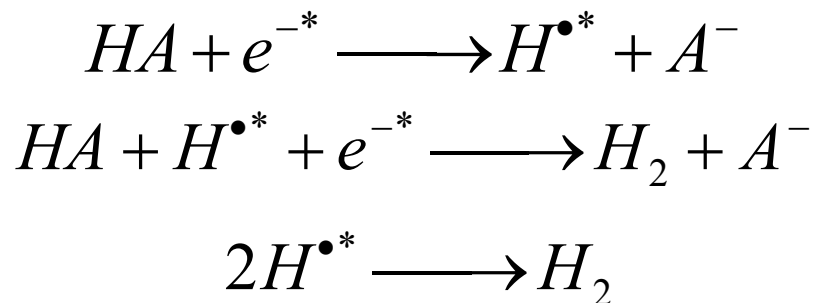
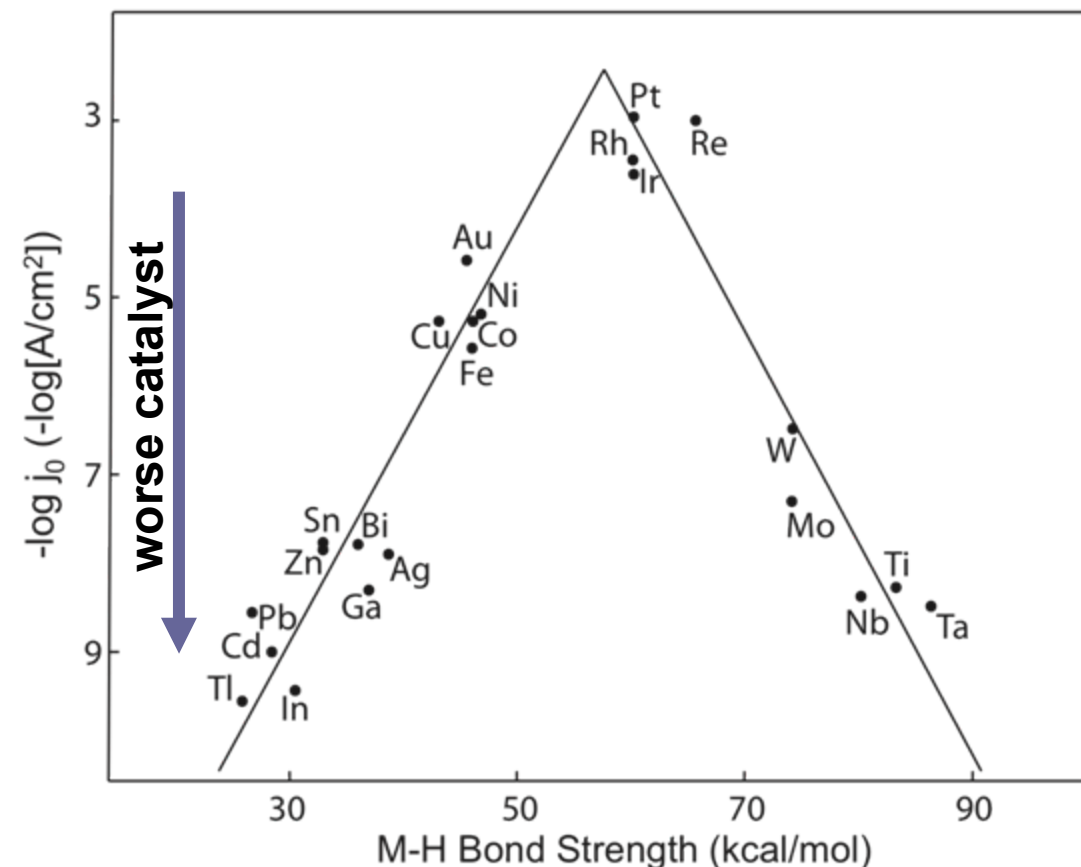
n' is the number of electrons transferred prior to the rate determining step.

Tafel slope gives mechanistic information (in principle!)



Hydrogen Evolution Reaction

Volcano Relation for Pure Metals

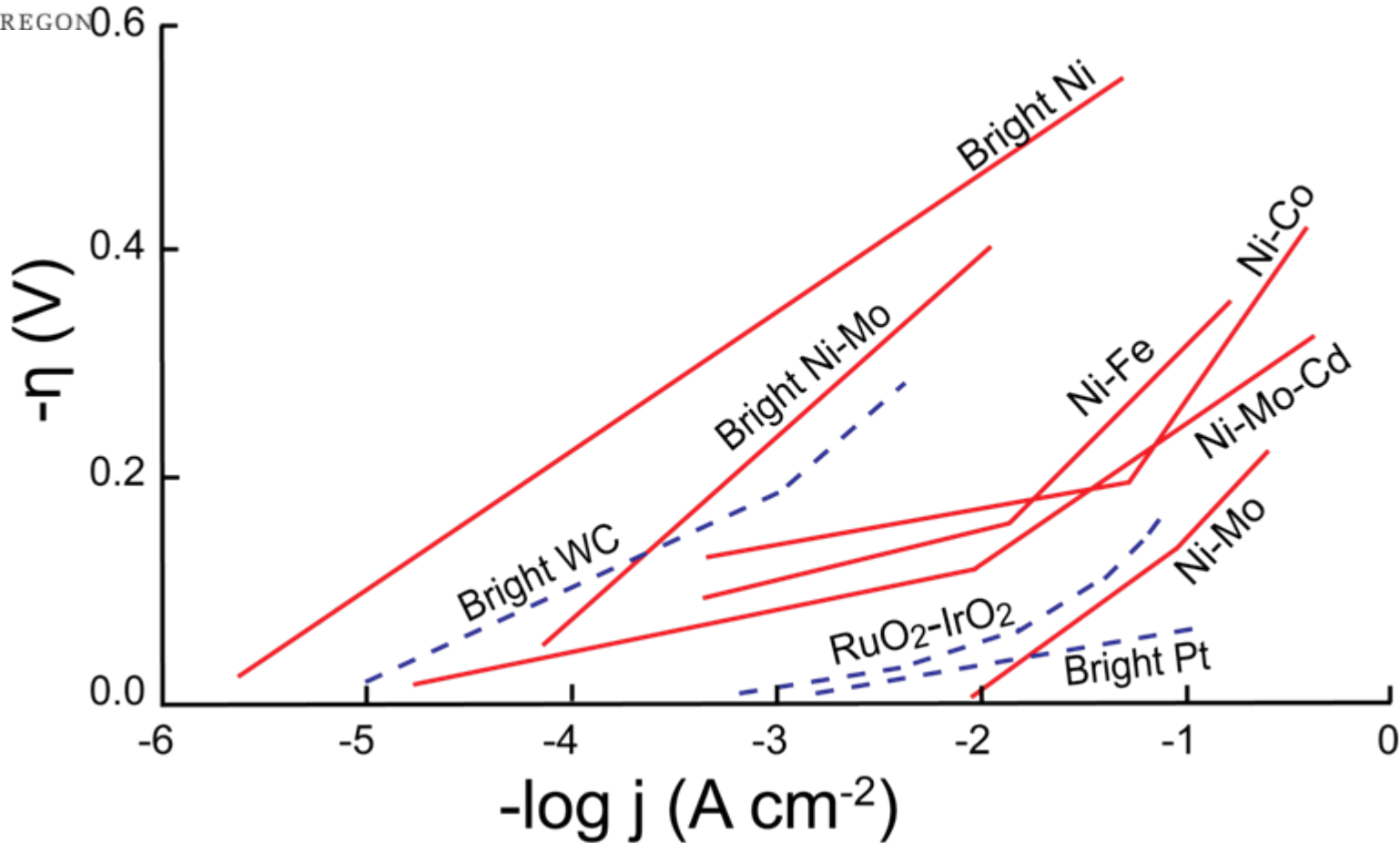


“Goldilocks” principle;
intermediate absorption
energy (here M-H) is not too
strong or too weak.

Trasatti, S. *J. Electroanal. Chem.* **1972**, 39, 163.



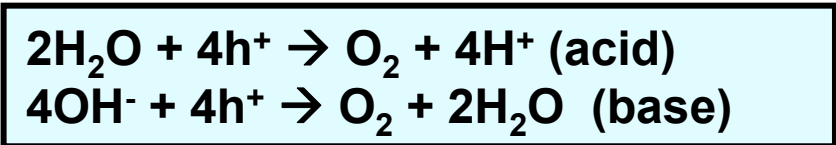
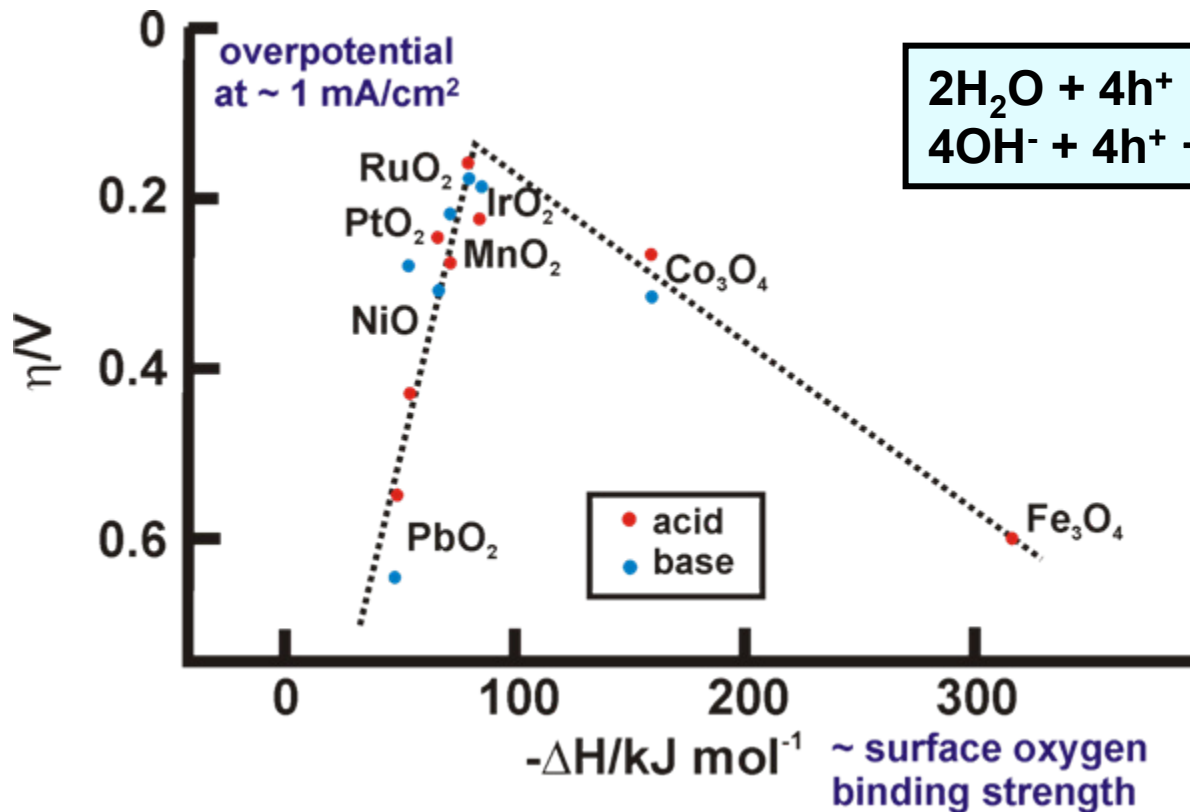
HER Overpotentials



- Pt is a phenomenally fast catalyst for HER.
- Much effort is applied to develop alternative catalysts to replace Pt.
- Different surface areas of materials makes comparison difficult.



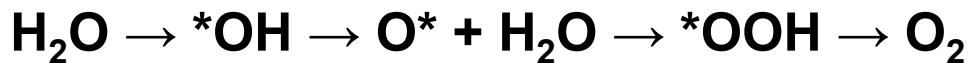
Large loss for driving water oxidation reaction kinetics



What determines the activity of an electrocatalyst?

How do we design catalysts?

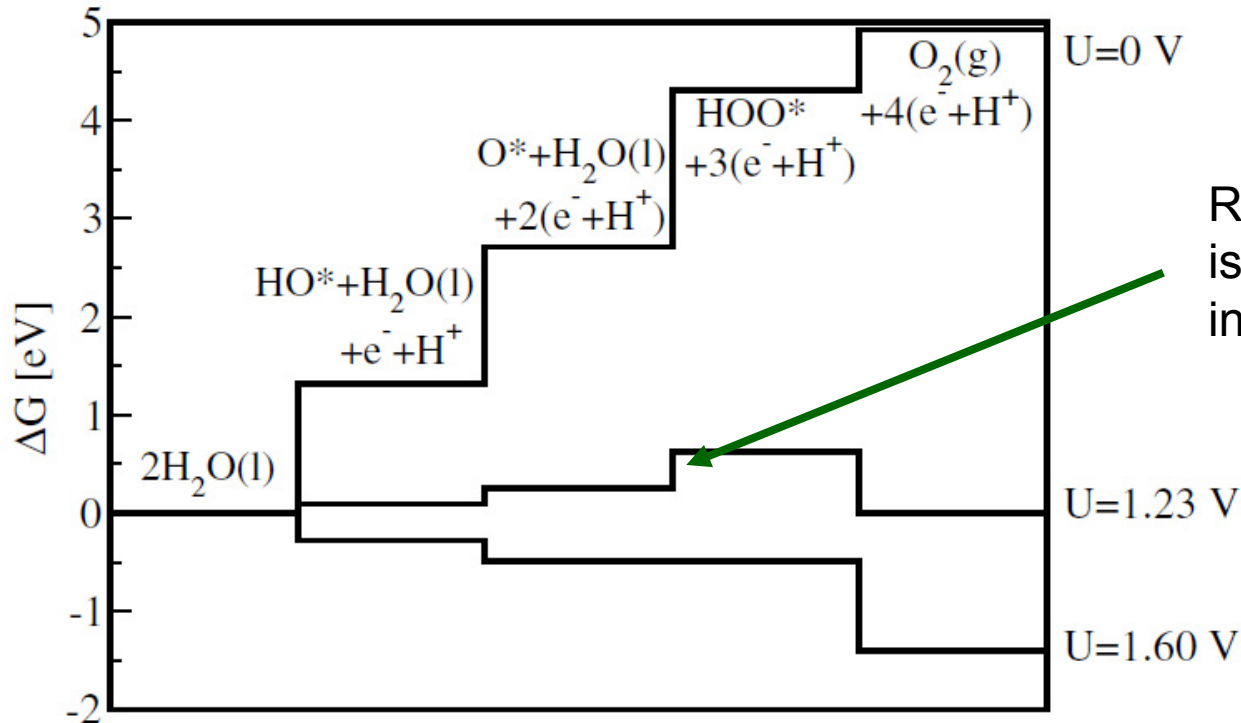
Complicated 4-step reaction!



* Indicates bonded to the surface

Trasatti. *Electrochim. Acta* **29** (11), 1503 (1984).
 Norskov et. al. *J. Electroanal. Chem.* **607** (1-2), 83 (2007).
 Suntivich, J.; et. al *Science* **2011**, 334, 1383-1385.

O Theory: electrocatalysis requires the stabilization of intermediates



Rate determining Step is the 3rd electron transfer in this case.

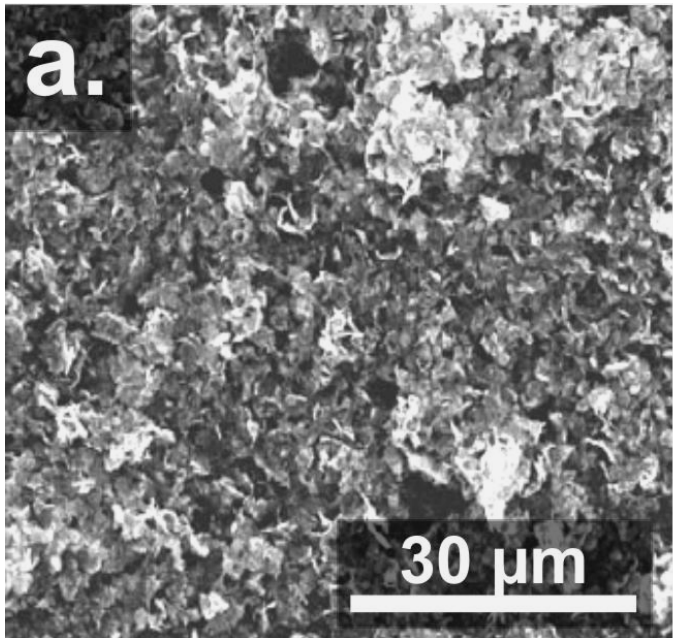


* Indicates bonded to the surface

(note: other reaction mechanisms can be drawn; for example requiring the recombination of two surface bound intermediates)

Rossmeisl, J.; Qu, Z.-W.; Zhu, H.; Kroas, G.-J.; Nørskov, J.K. *J. Electroanal. Chem.* **2007**, 607, 83 – 89.

Optimization vs. Design



SEM of typical “thick”
film electrocatalyst¹...

- High-surface area thick film
- Designed for maximum current per geometric area
- Dark colored – poorly suited for PEC

Role of composition, conductivity, and porosity?

What is the actual active component?
Complicated!

(1) Wang et. al., *Electrochimica Acta* 50 (2005) 2059–2064

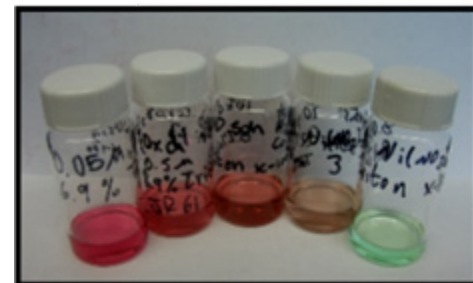
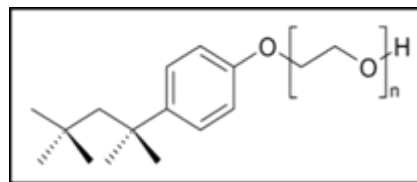
(2) Norskov, J. K.; Rossmeisl, J. Oxygen Evolution Electrocatalysis on Oxide Surfaces. *ChemCatChem* 2011, 3, 1159-1165.



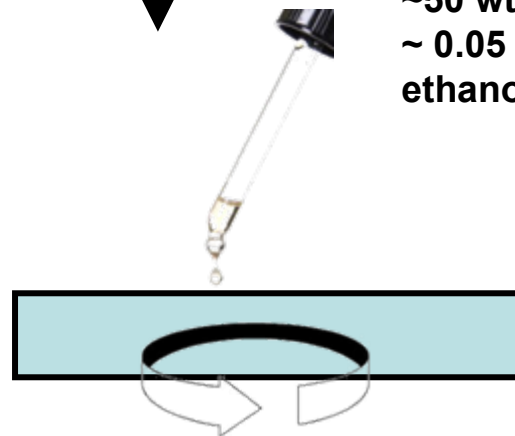
Solution-processed ultra-thin film catalysts

Advantages for fundamental study:

- Catalyst conductivity irrelevant
- Film composition controlled exactly by precursor solution
- Mass known
- Surface area controlled
- Facile gas and ion transport



~50 wt% surfactant
~ 0.05 M metal nitrate
ethanol



spincoating

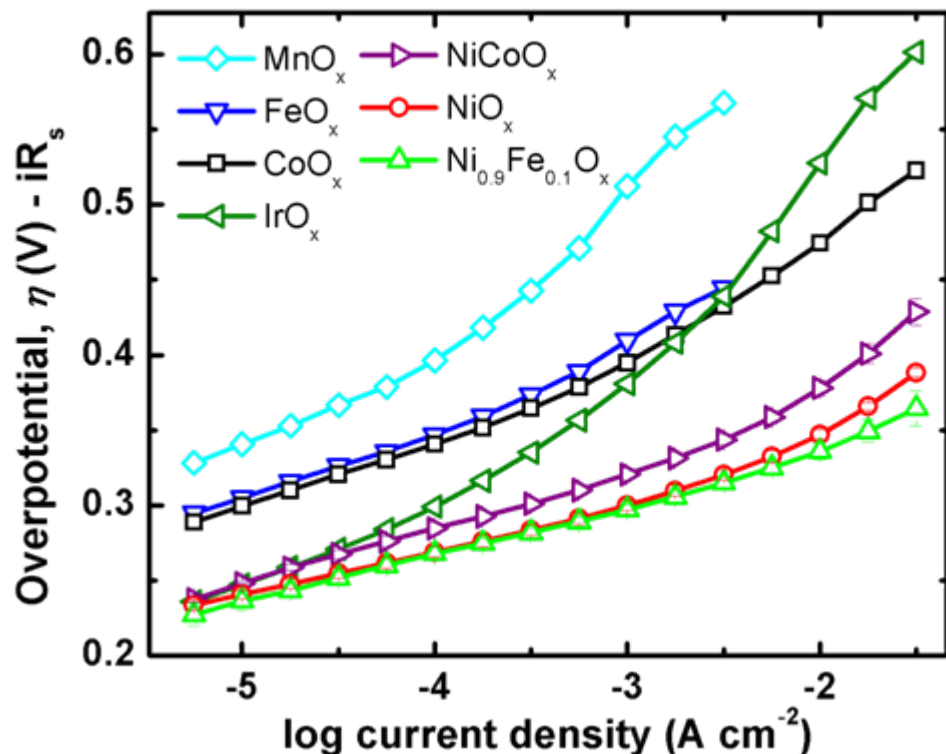
= Film



QCM crystal

O Thin Film OER Quantitative Comparison

UNIVERSITY OF OREGON



sample	$\eta @ J = 1$ mA cm^{-2} (mV)	loading $\mu\text{g cm}^{-2}$	at $\eta = 300$ mV	
			A g^{-1}	TOF (sec^{-1})
MnO_x	512	1.2	1.3	0.0003
FeO_x	409	1.7	4.5	0.0009
CoO_x	395	1.3	7.6	0.0016
IrO_x	381	4.2	24.2	0.014
$\text{Ni}_{0.5}\text{Co}_{0.5}\text{O}_x$	321	1.1	273	0.056
NiO_x	300	1.3	773	0.15
Fe:NiO_x	297	1.2	1009	0.20

TOF = # O₂ produced per metal per second

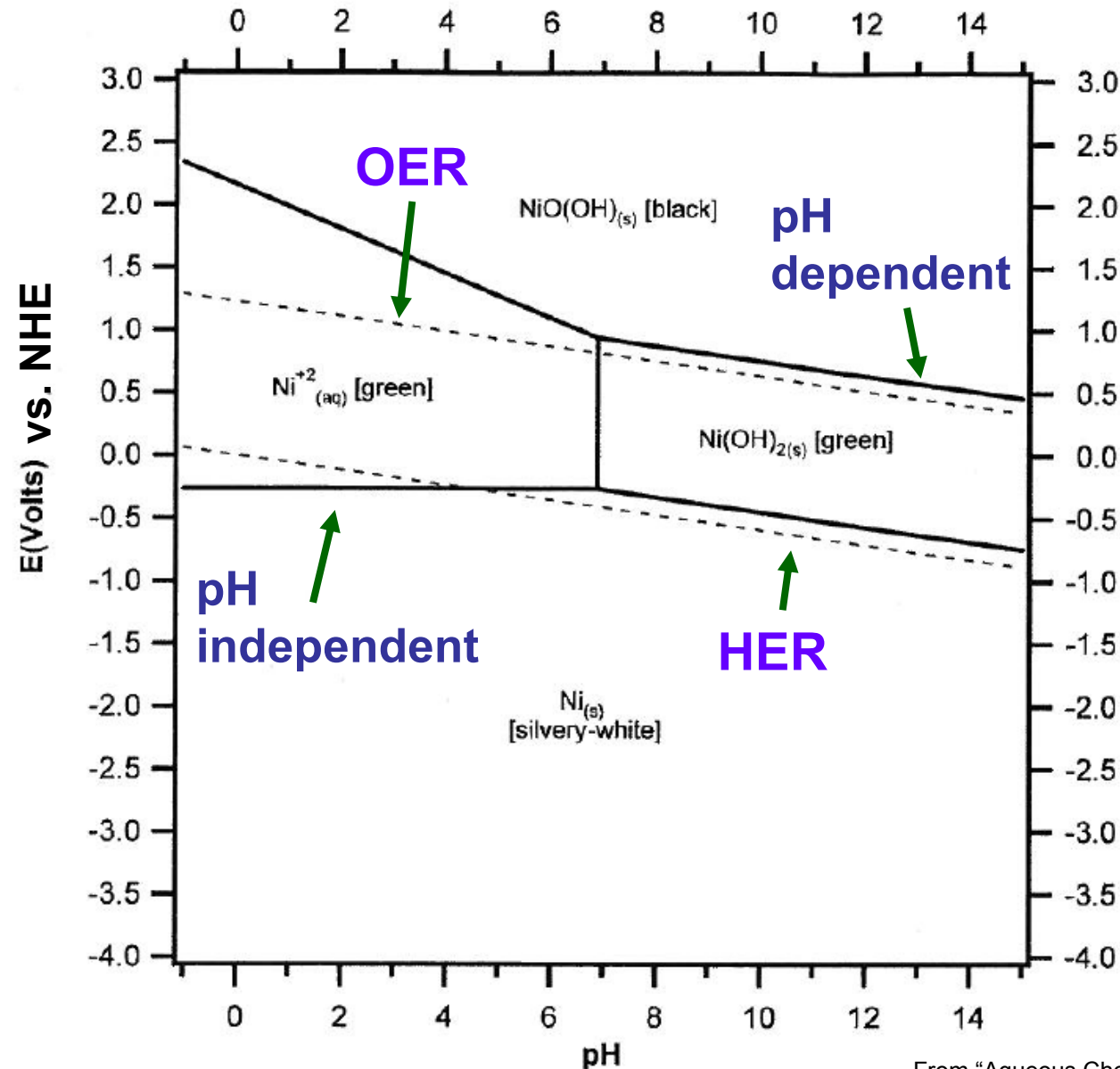
Fe:NiO_x >10x more active than IrO₂ and >100x more active than CoO_x

Why?

Trotochaud et. al. Submitted 2012.



Stability: Pourbaix Diagrams



Ni

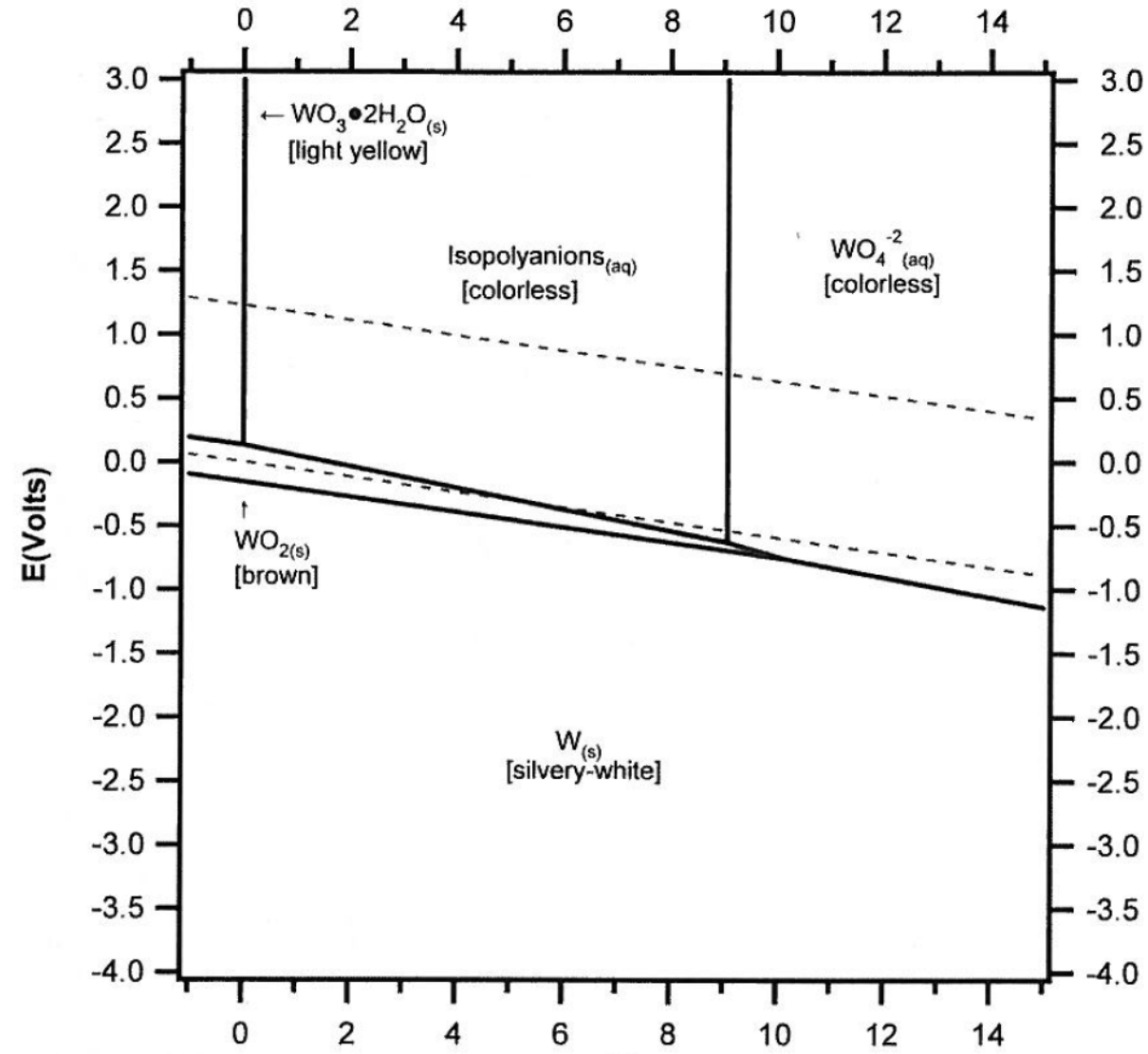
Based on free-energies of formation; potential-pH “predominance-area diagram”

When can NiO be used as an electrocatalyst for OER?

From “Aqueous Chemistry of the Elements” Schweitzer and Pesterfield.



Stability: Pourbaix Diagrams



W

Under what conditions can tungsten oxide (WO_3) be used as a photocatalyst?

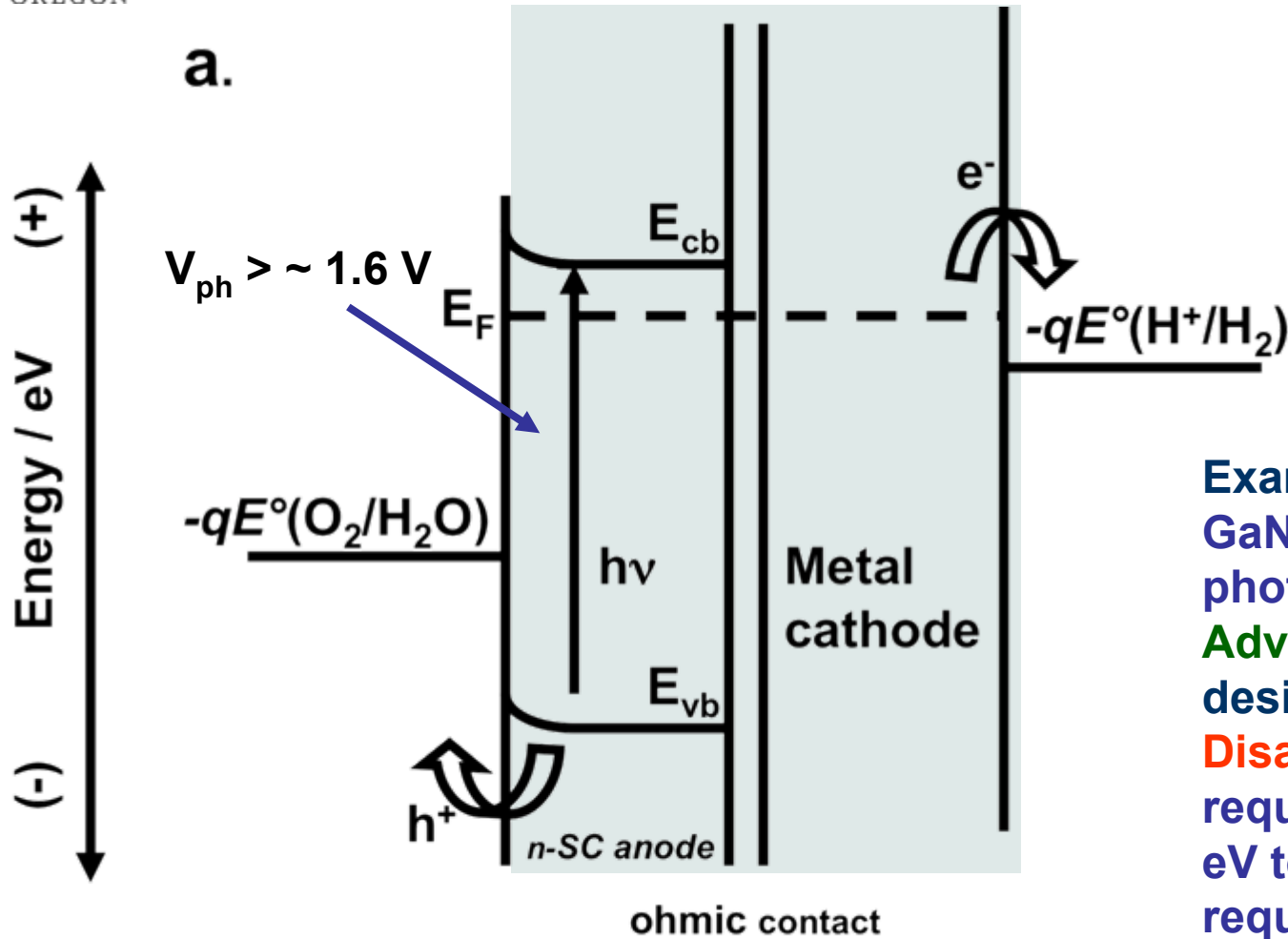
From "Aqueous Chemistry of the Elements" Schweitzer and Pesterfield.



Part III : Examples of integrated devices and some literature examples.



Energy Diagrams for Solar Water Splitting Devices: n-type photoanode



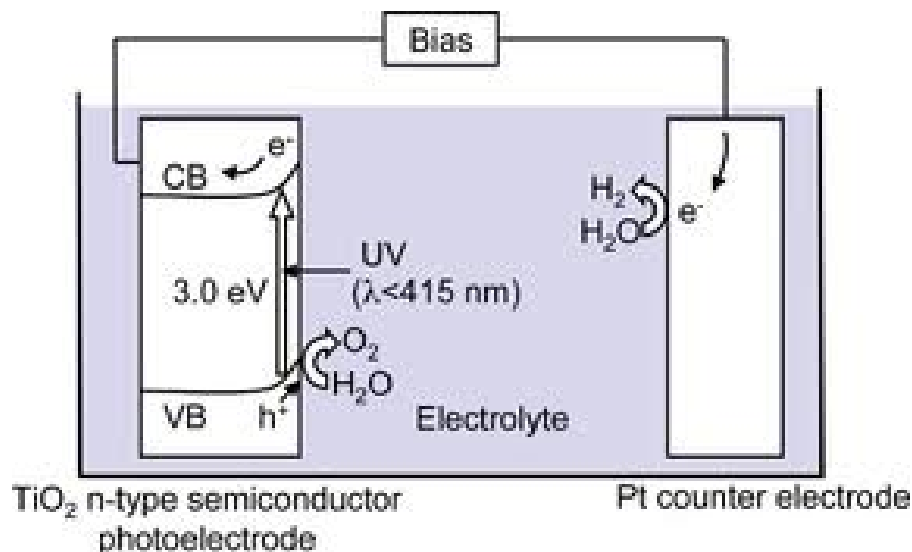
n-type photoanode PEC

Example: n- SrTiO₃ or GaN:ZnO photoelectrode.

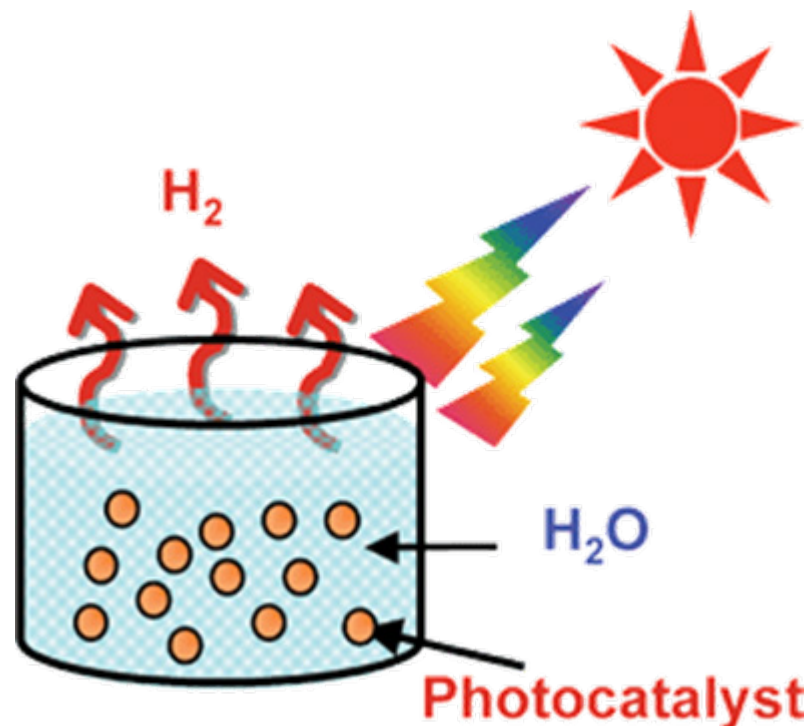
Advantage: Simple design. Cheap?

Disadvantage: requires large $E_g > 2.5 \text{ eV}$ to generate required photopotential

Wide Band Gap Photocatalysts



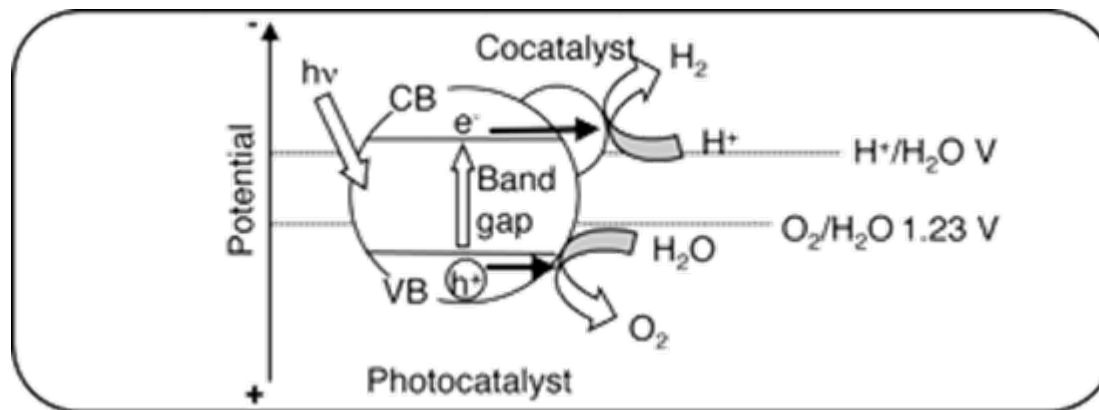
Photoelectrodes
("Fujishima – Honda Effect")



Dispersed nano/micropowders

1. Fujishima, A.; Honda, K. Electrochemical Photolysis of Water at a Semiconductor Electrode. *Nature* **1972**, *238*, 37-38.
2. Kumar, A.; Santangelo, P. G.; Lewis, N. S. Electrolysis of Water at SrTiO₃ Photoelectrodes - Distinguishing between the Statistical and Stochastic Formalisms for Electron-Transfer Processes in Fuel-Forming Photoelectrochemical Systems. *J. Phys. Chem.* **1992**, *96*, 834-842.
3. Kudo, A.; Miseki, Y. Heterogeneous photocatalyst materials for water splitting. *Chem. Soc. Rev.* **2009**, *38*, 253-278.

Powdered Photocatalysts

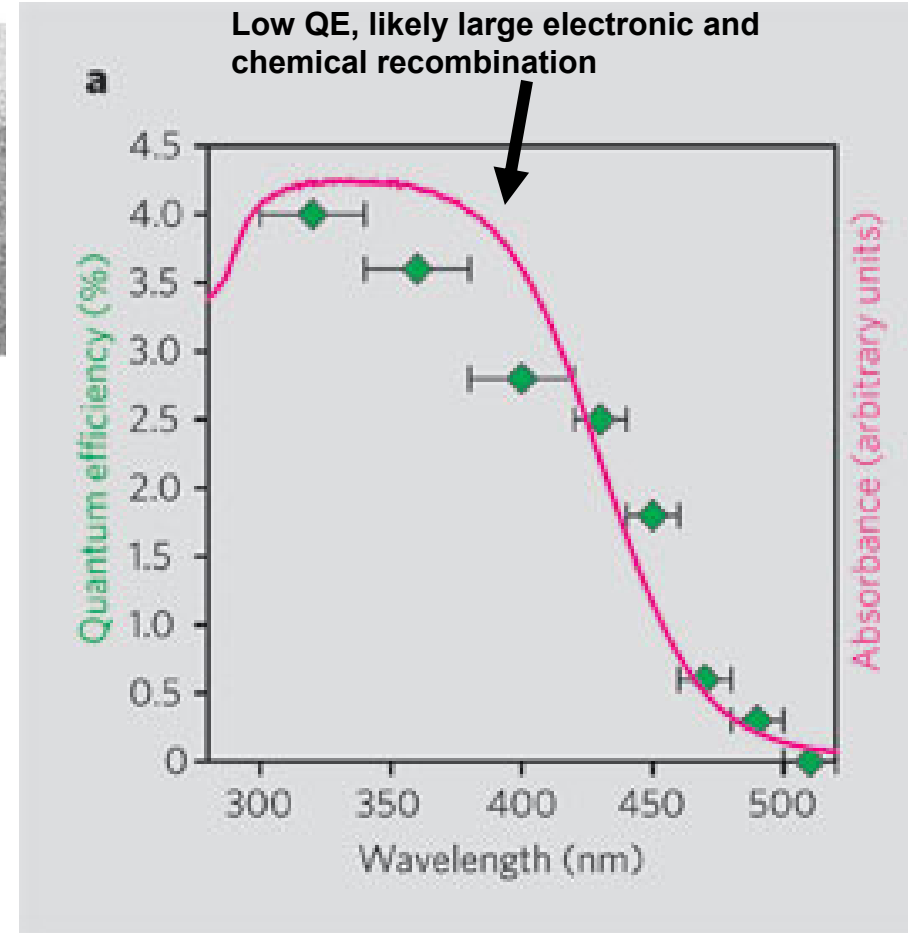
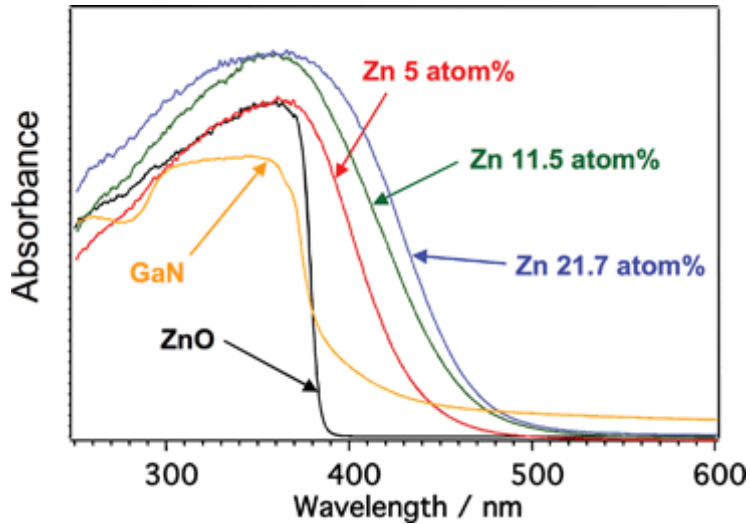
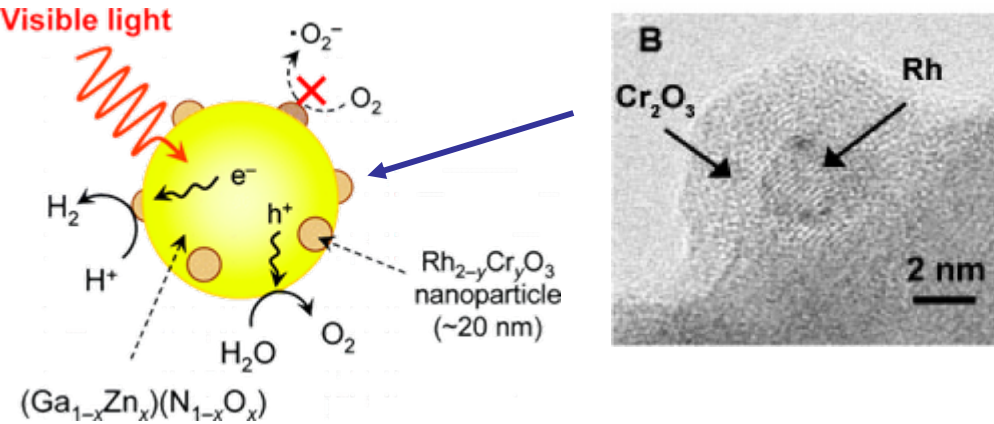


Advantage: No support, high surface area, easy to scale-up.

Disadvantage: 1. Single junction cell requires large $E_g > 2.5$ eV to generate required photopotential; fundamentally inefficient with solar spectrum. 2. Separation of H_2 and O_2 flammable mixture difficult. How to prevent reverse electrochemical reaction?

O Example: Visible light activity via tuning materials properties

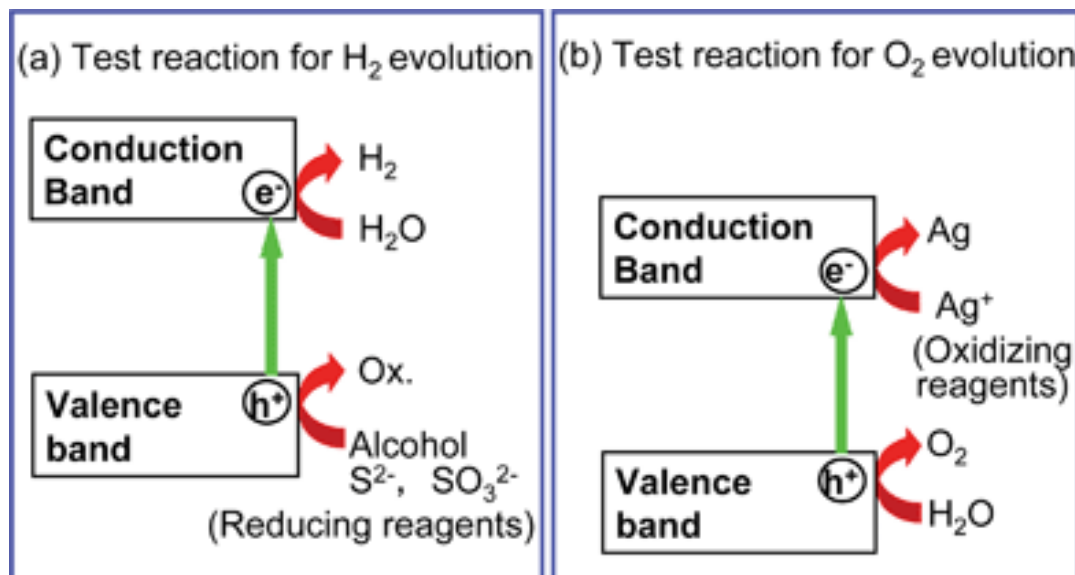
UNIVERSITY OF OREGON



(1) Kudo, A.; Miseki, Y. Heterogeneous photocatalyst materials for water splitting. *Chem. Soc. Rev.* **2009**, *38*, 253-278.

(2) Maeda, K.; Teramura, K.; Lu, D. L.; Takata, T.; Saito, N.; Inoue, Y.; Domen, K. Photocatalyst releasing hydrogen from water - Enhancing catalytic performance holds promise for hydrogen production by water splitting in sunlight. *Nature* **2006**, *440*, 295-295.

(3) Maeda, K.; Domen, K. New Non-Oxide Photocatalysts Designed for Overall Water Splitting under Visible Light. *J. Phys. Chem. C* **2007**, *111*, 7851-7861.



Often used to interrogate half-reactions individually.

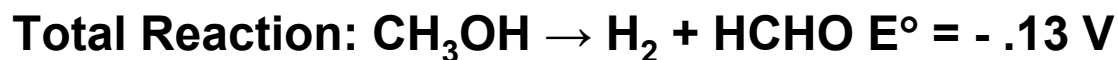
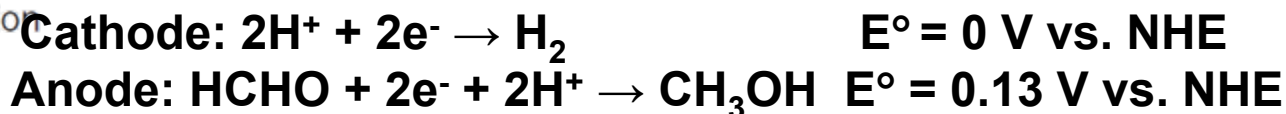
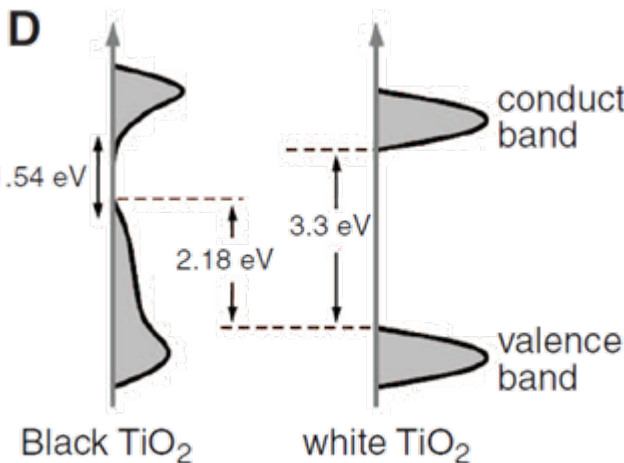
However: Overall reaction can be energetically neutral or even downhill.
 Hard to test semiconductor photovoltage generation, which is important to split water.





“The energy conversion efficiency for solar hydrogen production, defined as the ratio between the energy of solar-produced hydrogen and the energy of the incident sunlight, reached 24% for disorder-engineered black TiO₂ nanocrystals.”

But a sacrificial agent was used:



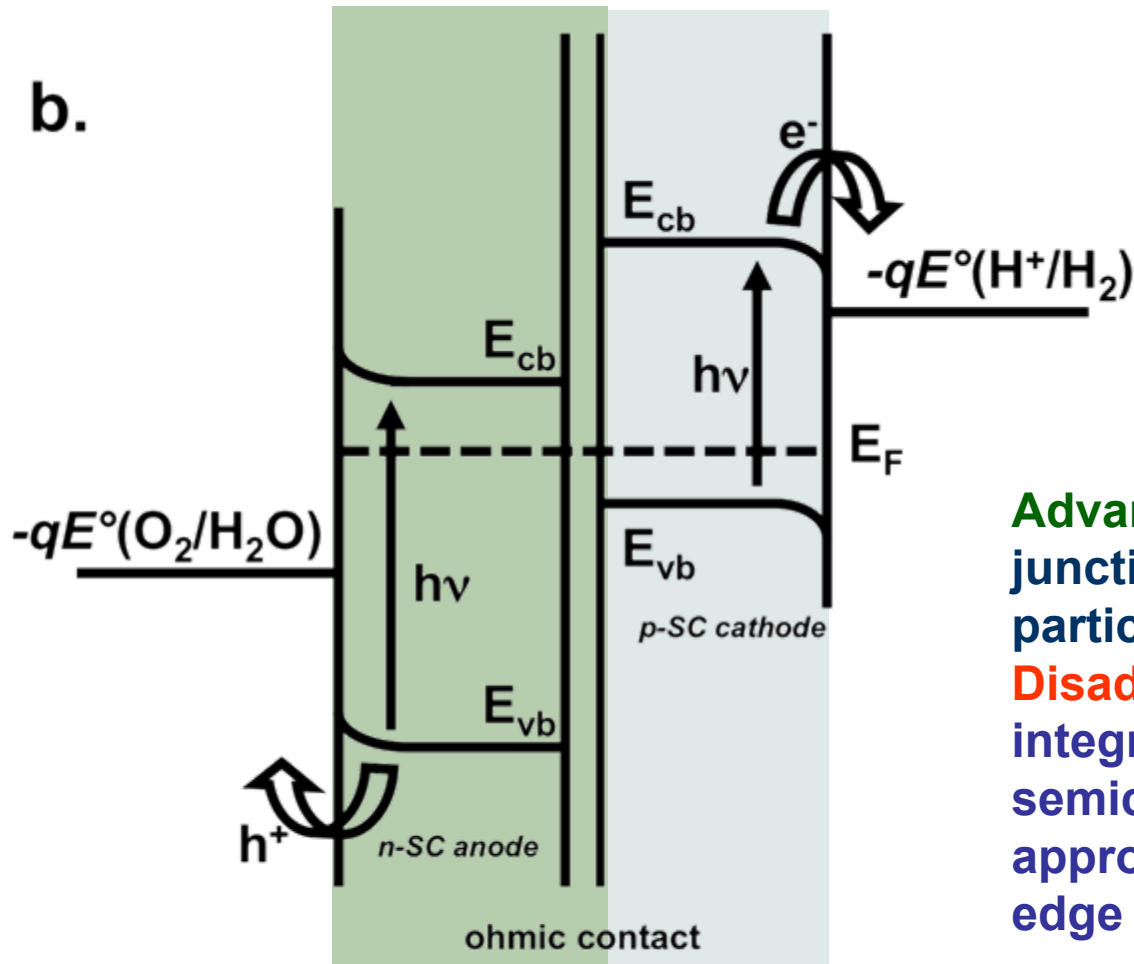
Almost zero net energy storage in this system.

Could map photovoltage generation using a series of sacrificial reagents with different chemical potentials.

Chen, X.; Liu, L.; Yu, P. Y.; Mao, S. S. Increasing Solar Absorption for Photocatalysis with Black Hydrogenated Titanium Dioxide Nanocrystals. *Science* **2011**, *331*, 746-750.



Energy Diagrams for Solar Water Splitting Devices – p/n PEC z-scheme



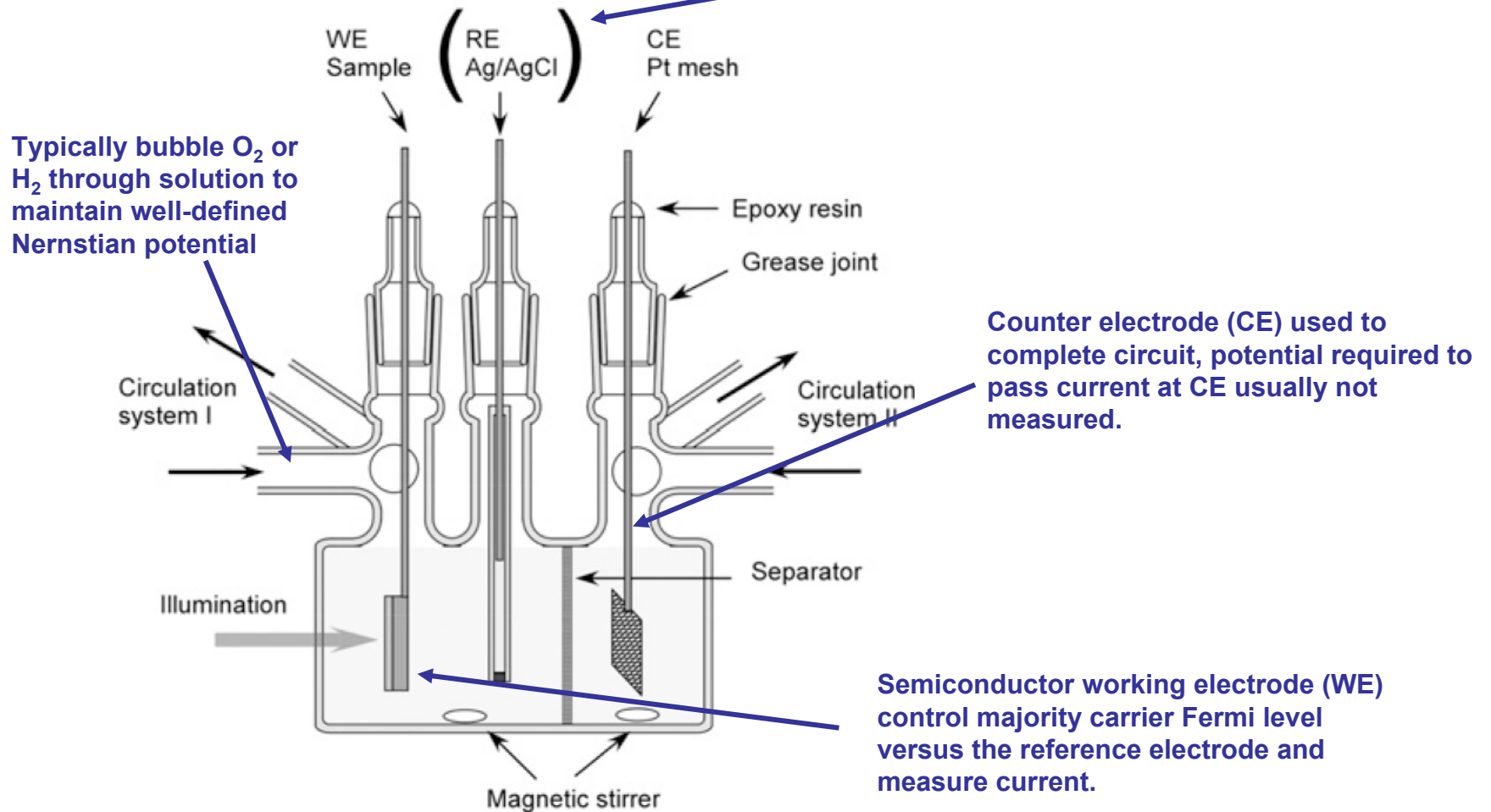
Advantage: no pn junctions, could be particulate based
Disadvantage: need to integrate two high-quality semiconductors with appropriate E_g and band edge positions.

p/n-PEC (photoanode/cathode cell)



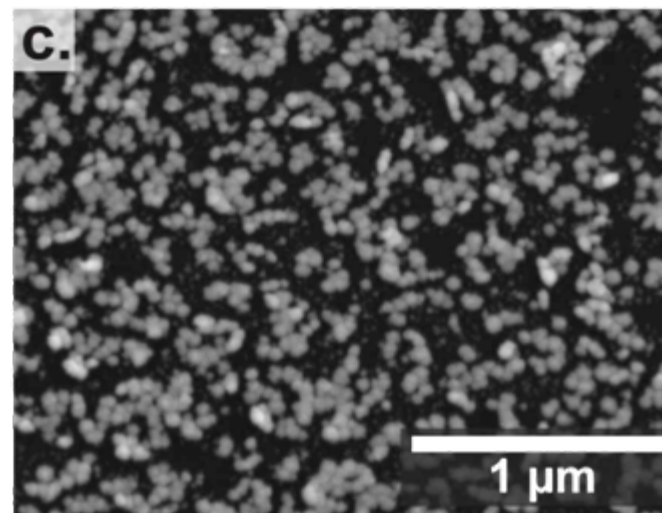
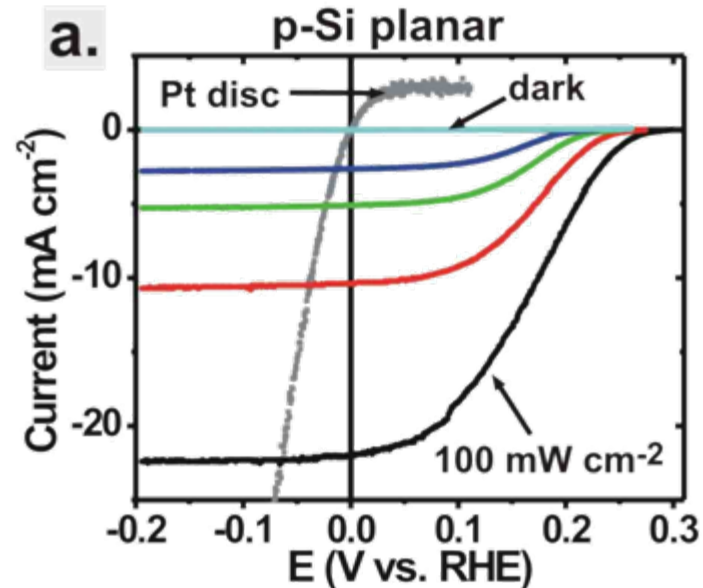
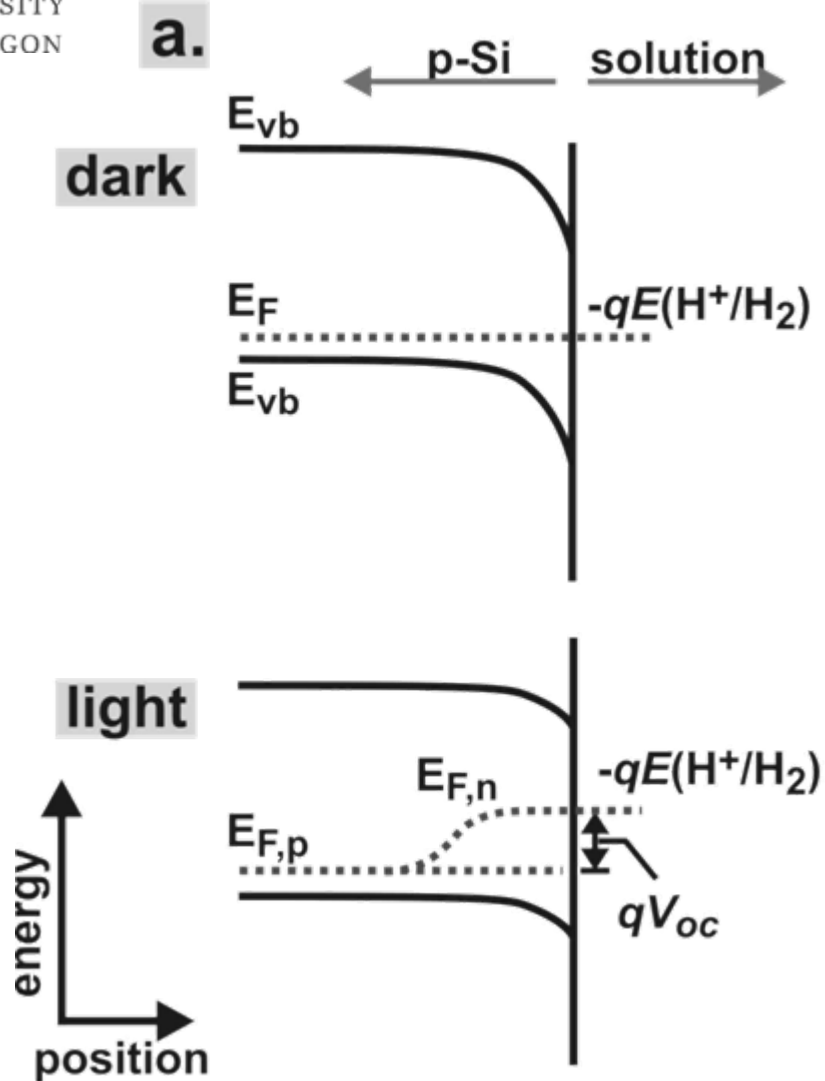
Individual component testing using a 3-electrode potentiostat

Double Vessel Cell



Chen, Z. B.; Jaramillo, T. F.; et. al. *J. Mater. Res.* **2010**, 25, 3-16.

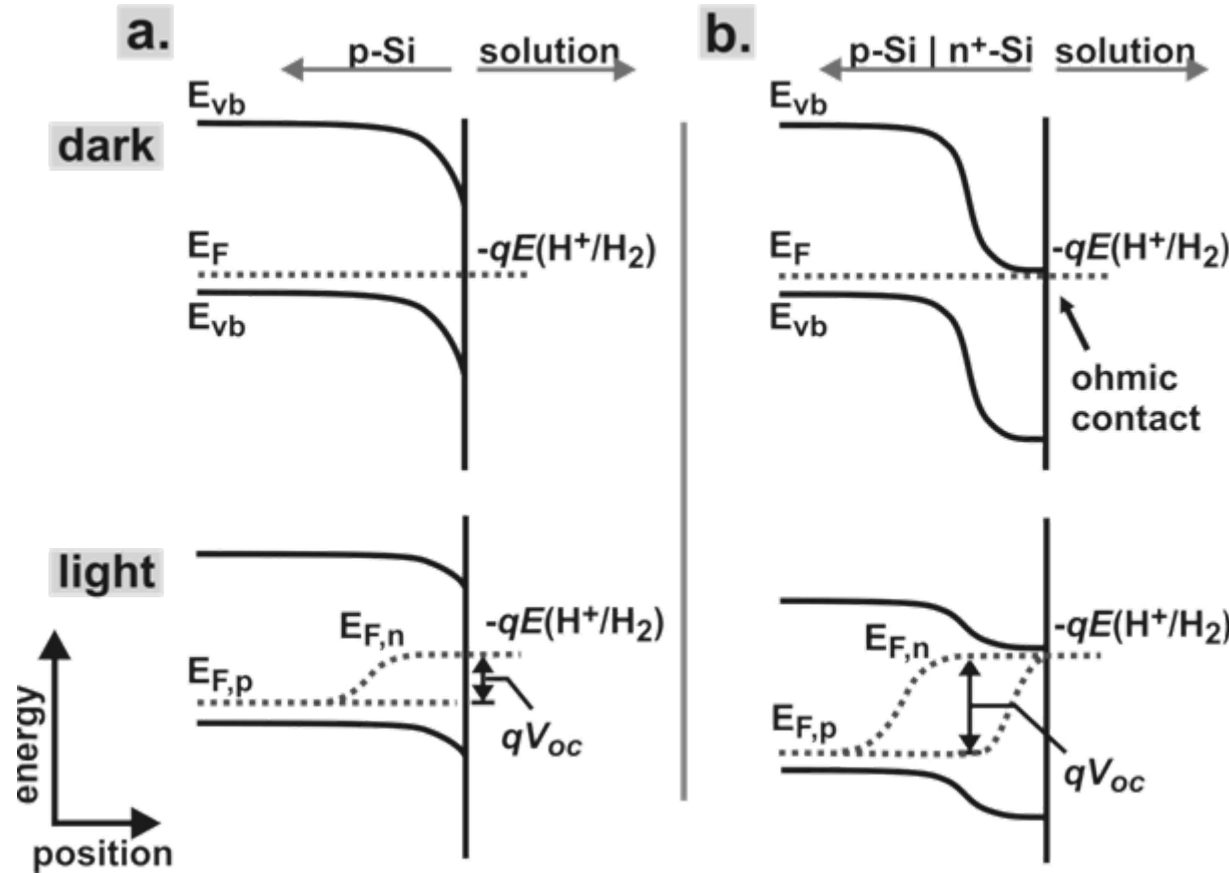
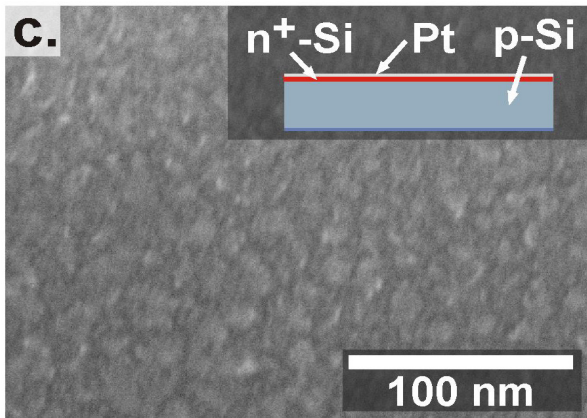
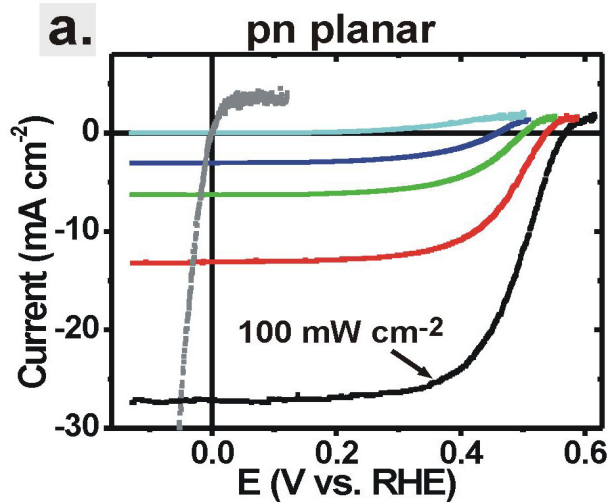
p-Si Photocathode Example



Boettcher, S. W.; Warren, E. L.; Putnam, M. C.; Santori, E. A.; Turner-Evans, D.; Kelzenberg, M. D.; Walter, M. G.; McKone, J. R.; Brunschwig, B. S.; Atwater, H. A.; Lewis, N. S. Photoelectrochemical Hydrogen Evolution Using Si Microwire Arrays. *J. Am. Chem. Soc.* **2011**, *133*, 1216-1219.



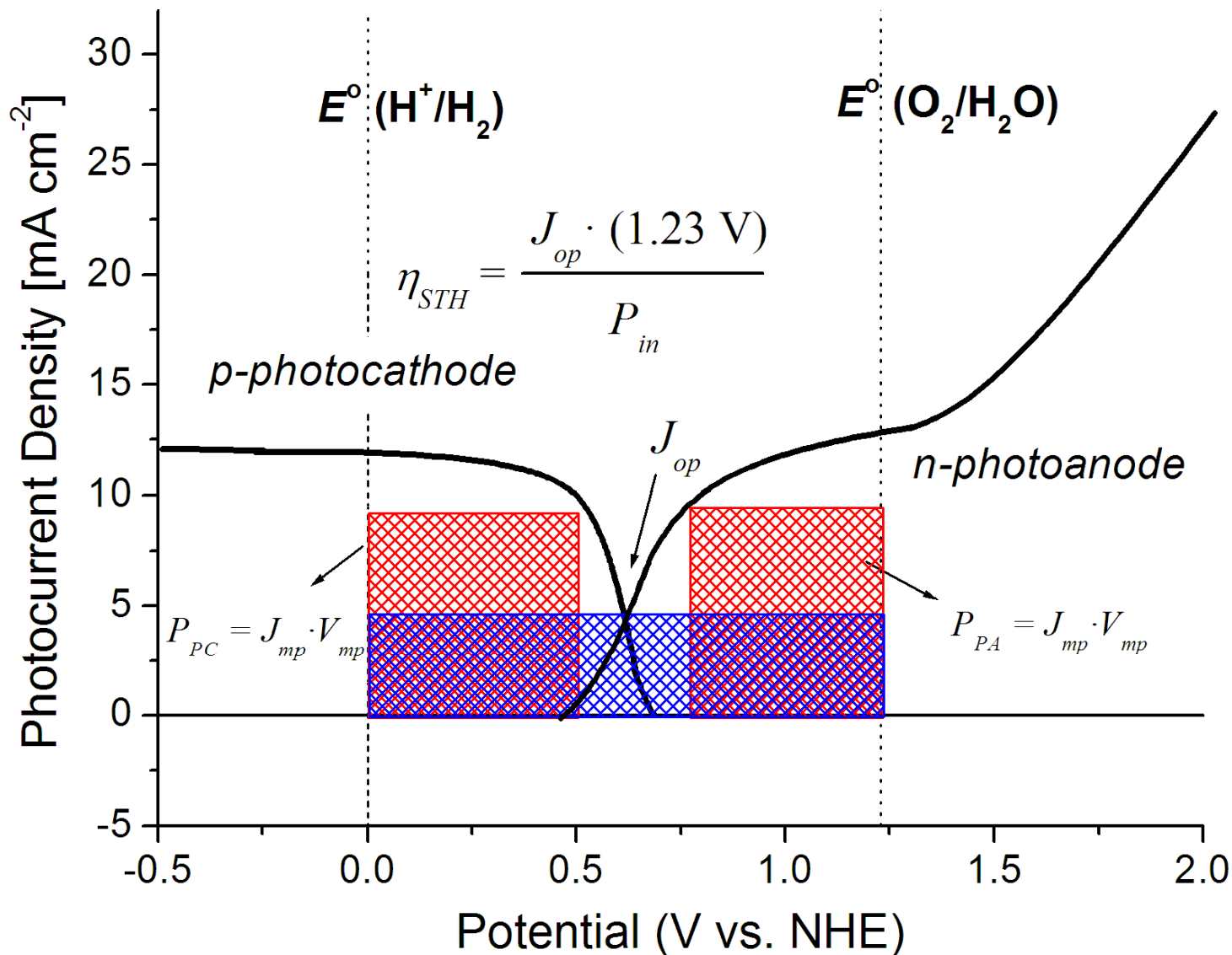
pn⁺ Si photocathode





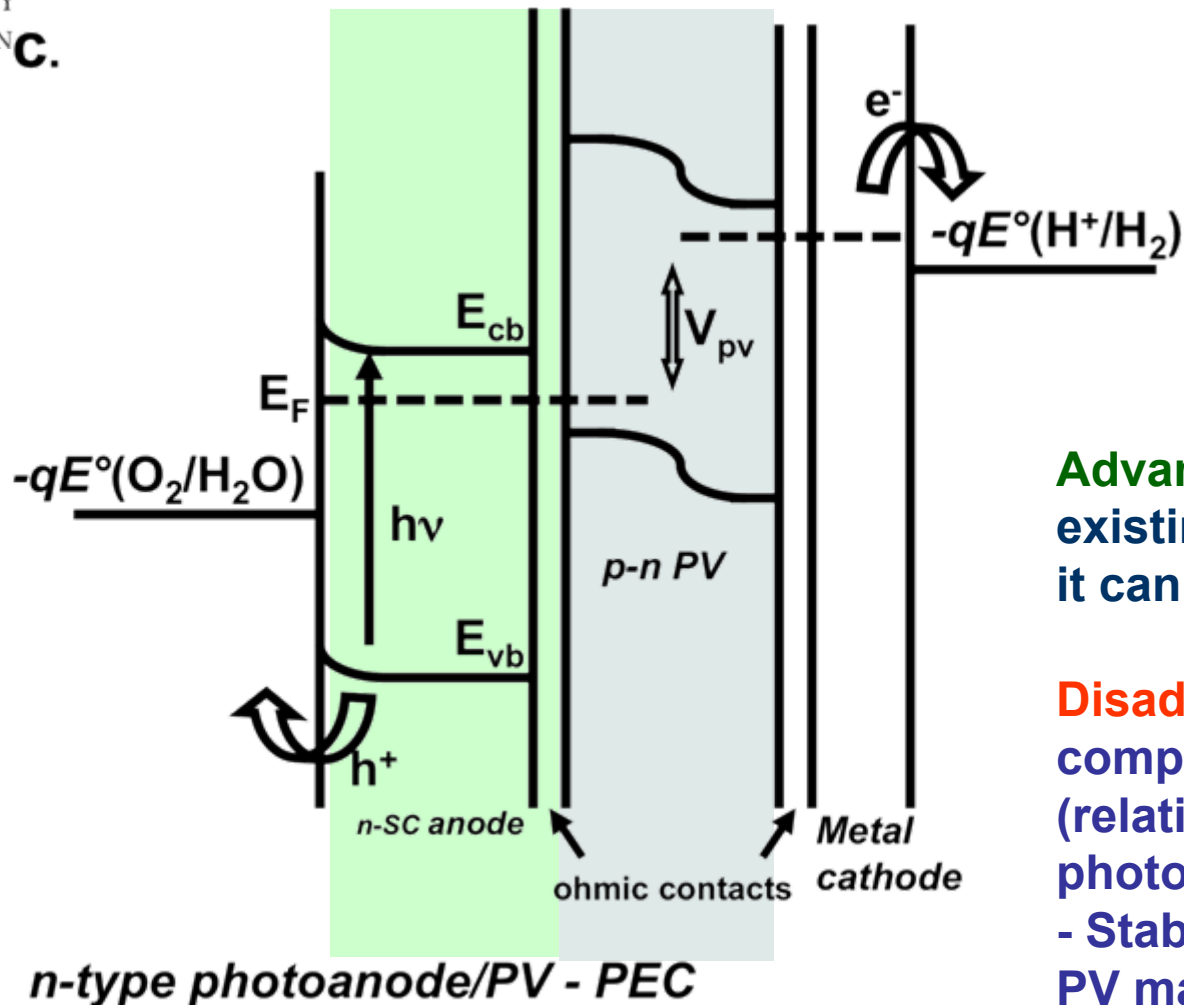
Overlaid J-E behavior System Performance

UNIVERSITY
OF OREGON



Walter, M.; Warren, E.; McKone, J.; Boettcher, S. W.; Qixi, M.; Santori, L.; Lewis, N. S. Solar Water Splitting Cells. *Chem. Rev.* **2010**, *110*, 6446-6473.

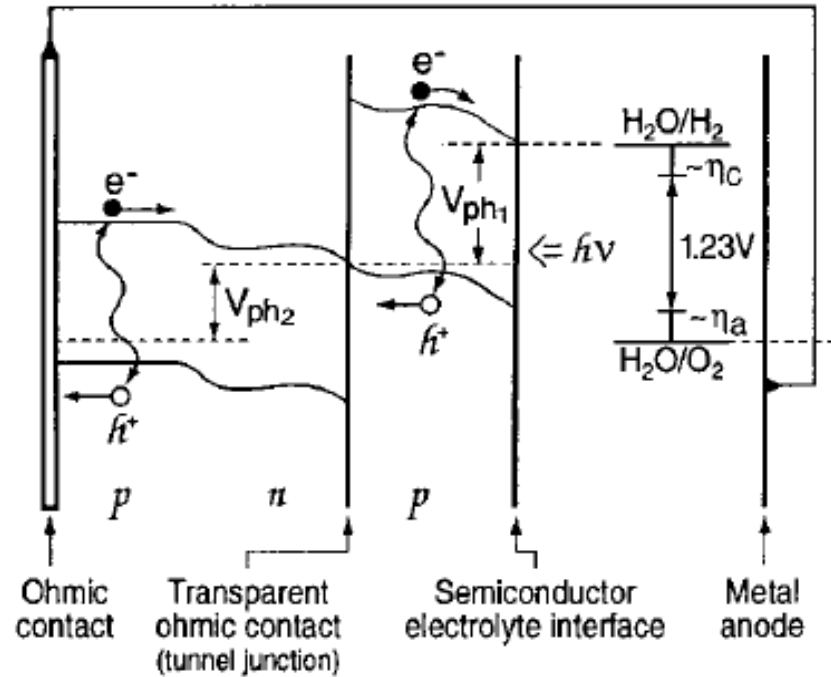
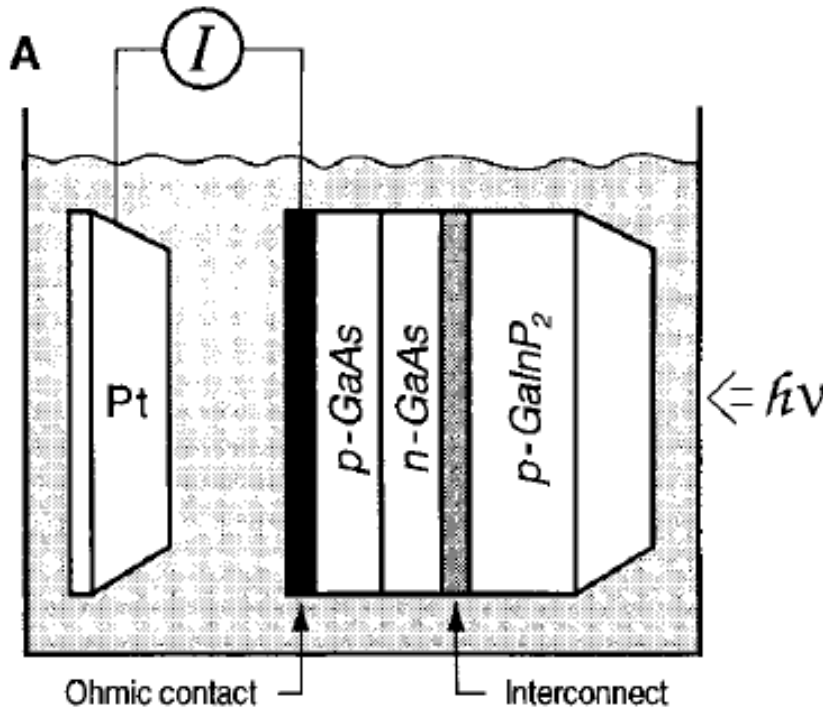
Cells with integrated PV/PEC junctions



Advantage: build on existing solar technology; it can work now

Disadvantage: - Increased complexity from already (relatively) expensive photovoltaic device.
 - Stability of conventional PV materials in water for 30 yrs questionable.

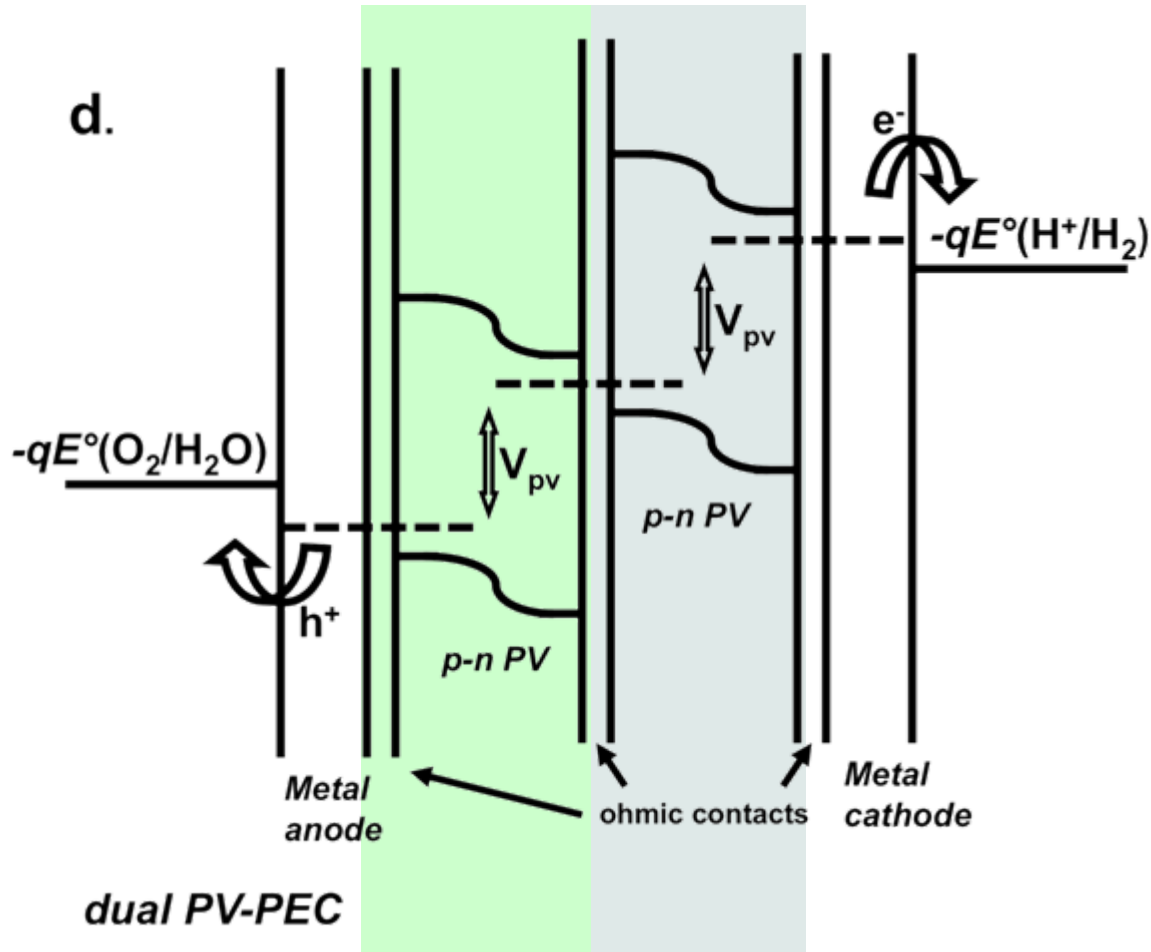
Ex. "Turner" NREL Water Splitting Cell



12.4% efficiency (STH) with a cost of ~\$10,000 m⁻² and limited stability

Khaselev, O.; Turner, J. A. A Monolithic Photovoltaic-Photoelectrochemical Device for Hydrogen Production via Water Splitting. *Science* **1998**, *280*, 425-427.

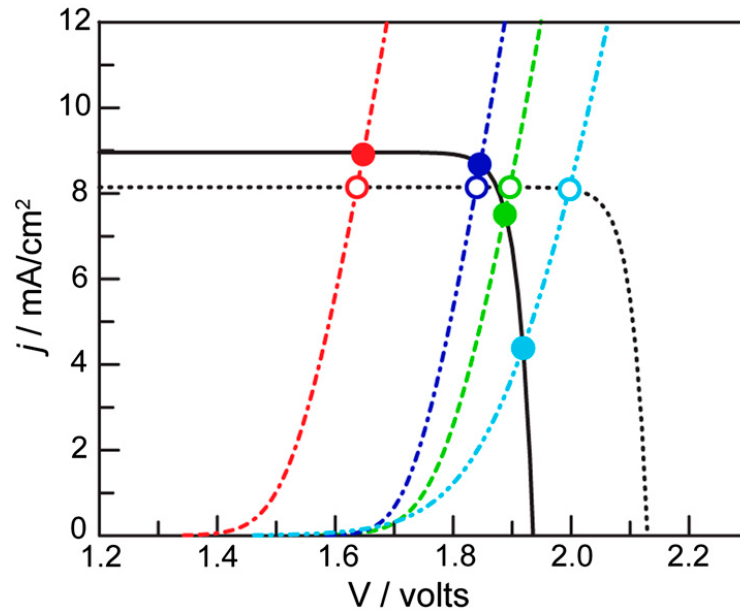
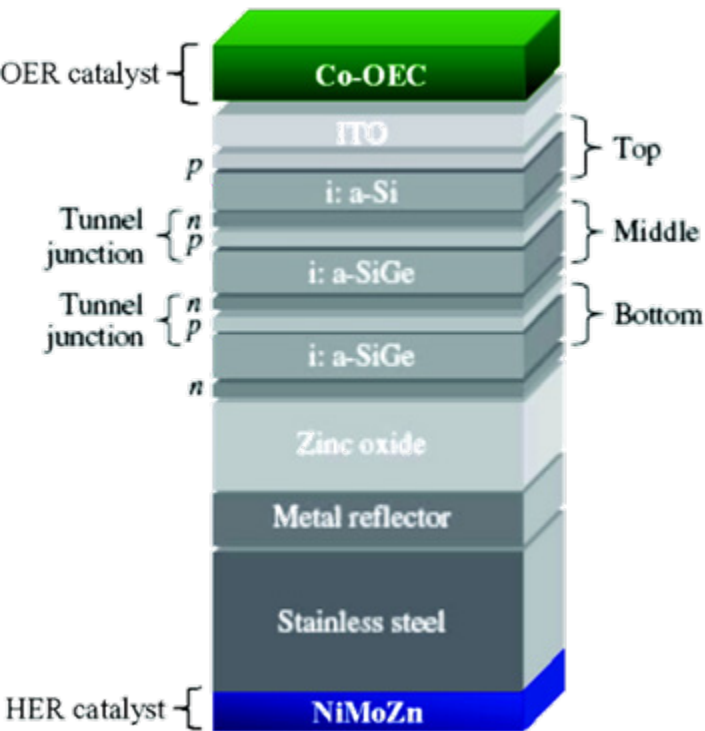
Buried PV-electrolyzer combination



Advantage: build on existing solar technology, wireless design reduces cost relative to separate PV + electrolyzer?

Disadvantage: Multijunction solar cells are expensive (III-V) or inefficient (a-Si), protection of surface needed, catalyst integration.

Integrated PV-Electrolysis “Artificial Leaf”



Challenge: Triple-junction a-Si solar cell too expensive and efficiency too low (<5%). Ohmic losses are significant without engineering pathways for ion transport. **Need new low cost solar materials and catalysts with better transparency.**

<http://www.nature.com/news/artificial-leaf-hits-development-hurdle-1.10703>

- (1) Rocheleau, R. E.; Miller, E. L.; Misra, A. High-efficiency photoelectrochemical hydrogen production using multijunction amorphous silicon photoelectrodes. *Energy Fuels* **1998**, *12*, 3-10.
- (2) Reece, S. Y.; Hamel, J. A.; Sung, K.; Jarvi, T. D.; Esswein, A. J.; Pijpers, J. J. H.; Nocera, D. G. Wireless Solar Water Splitting Using Silicon-Based Semiconductors and Earth-Abundant Catalysts. *Science* **2011**, *334*, 645-648.
- (3) Nocera, D. G. The Artificial Leaf. *Acc. Chem. Res.* **2012**, *45*, 767-776.



Calculation of Overall Efficiencies

Based on total measured Hydrogen output:

$$STH = \left[\frac{(\text{mmol H}_2/\text{s}) \times (237 \text{ kJ/mol})}{P_{\text{total}} (\text{mW/cm}^2) \times \text{Area} (\text{cm}^2)} \right]_{\text{AM 1.5 G}}$$

Based on measured current (in 2-electrode configuration)

$$STH = \left[\frac{|j_{SC} (\text{mA/cm}^2)| \times (1.23 \text{ V}) \times \eta_F}{P_{\text{total}} (\text{mW/cm}^2)} \right]_{\text{AM 1.5 G}}$$

STH = solar-to-hydrogen efficiency

**Faradaic
efficiency**



UNIVERSITY OF OREGON

Acknowledgements

To all the mentors and co-workers!

"If I have seen further, it is by standing on the shoulders of giants"
- Isaac Newton.

Boettcher Group Summer 2012



T.J. Mills

Lena Trotochaud



Basic Energy Science
Solar Photochemistry



Young Professor Program



ONAMI
OREGON NANOSCIENCE AND
MICROTECHNOLOGIES INSTITUTE



Center for
Sustainable Materials Chemistry

